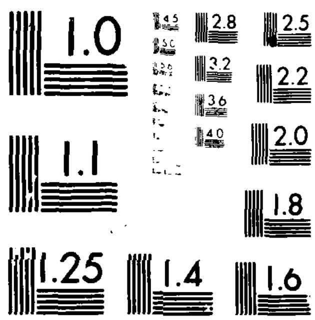
AD-A084 927 AERONAUTICAL RESEARCH INST OF SWEDEN STOCKHOLM F/G 20/4
INVESTIGATION OF MODELING CONCEPTS FOR PLUME-AFTERBODY FLOW INT--ETC(U)
FEB 79 S NYBERG, J AGRELL, T HEVRENG DAERO-78-G-028

UNCLASSIFIED NL

1 OF 1
AD
A084927

END
DATE
FILMED
7-80
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

INVESTIGATION OF MODELING CONCEPTS FOR PLUME-AFTERBODY FLOW INTERACTIONS

1st Annual Technical Report

by

S.-E Nyberg
J. Agrell
T. Hevreng

February 1979

EUROPEAN RESEARCH OFFICE
United States Army
London England

GRANT NUMBER DA-ERO-78-G-028

Grantee: Georg Drougge, Dr., Deputy Director
THE AERONAUTICAL RESEARCH INSTITUTE OF SWEDEN (FFA)
Box 1121, S-161 11 BROMMA , Sweden

This research has been sponsored jointly by the US Army European Research Office and by the FFA.

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

R&D 2515

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO. AD-A084927

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

6

Investigation of Modeling Concepts for Plume-Afterbody Flow Interactions,

5. ~~TYPE OF REPORT & PERIOD COVERED~~

9

Annual Report, no. 1,
Jan 78 - Jan 79,

6. ~~PERFORMING ORG. REPORT NUMBER~~

7. AUTHOR(s)

10

S.E./Nyberg, J./Agrell, T./Hevreng

8. ~~CONTRACT OR GRANT NUMBER(s)~~

15

DAERO-78-G-028 new

9. PERFORMING ORGANIZATION NAME AND ADDRESS

The Aeronautical Research Institute of Sweden, Bromma, Sweden

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

16

6.11.02A-1T161102BH57-06-00-715

11. CONTROLLING OFFICE NAME AND ADDRESS

US Army R&S Gp (Eur)
Box 65, FPO NY 09510

17 06

12. REPORT DATE

11

Feb [redacted] 79

13. NUMBER OF PAGES

54

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

008550

12 56

15. SECURITY CLASS. (of this report)

UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release, Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Rocket Motor Plumes
Jet Engine Plumes
Plume Afterbody
Plume Models
Plume Simulations
Exhaust Plumes
Exhaust Models

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The long-term objective is to critically evaluate the merits and limitations of plume modelling techniques. ~~During the first year of the three-year study,~~ preparations for the experimental investigation and computer program developments have been carried out. The design and construction of a facility for superheated Freon of high pressure to be used for jet plume simulation have been accomplished. Shake-down testing of the facility has started.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 008550

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. Abstract Contd.

A strut supported axi-symmetric model, extensively used in previous plume-afterbody flow investigations, has been modified for tests with heated Freon. Two propulsion nozzles for calibration tests and three nozzles for modelling tests have been constructed. This has been done in cooperation with the University of Illinois, where the internal flow characteristics for one of the nozzles have also been measured and found to be in excellent agreement with the computed predictions.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

INVESTIGATION OF MODELING CONCEPTS FOR PLUME-AFTERBODY FLOW INTERACTIONS

1st Annual Technical Report

by

S.-E. Nyberg

J. Agrell

T. Hevreng

SUMMARY

A three year program for investigation of plume-afterbody flow interactions to obtain data, such that critical evaluation of the merits and limitations of plume modeling techniques can be accomplished, has been undertaken by the FFA in close cooperation with the University of Illinois. During the first year, which this report covers, preparations for the experimental investigation and computer program developments have been carried out. The design and construction of a facility for superheated Freon of high pressure to be used for jet plume simulation have been accomplished. Shake-down testing of the facility has started.

A strut supported axi-symmetric model, extensively used in previous plume-afterbody flow investigations, has been modified for tests with heated Freon. Two propulsion nozzles for calibration tests and three nozzles for modeling tests have been constructed. This has been done in cooperation with the University of Illinois, where the internal flow characteristics for one of the nozzles have also been measured and found to be in excellent agreement with the computed predictions.

LIST OF CONTENTS Page

LIST OF ILLUSTRATIONS

NOMENCLATURE

H	enthalpy
M	Mach number
P, p	pressure
R^*	nozzle radius at throat
R_c	radius of wall curvature of nozzle throat
R_e	nozzle radius at exit
γ	ratio of specific heats
θ	wall angle

Subscripts

e	condition at nozzle exit
E	external flow condition
F	condition at the plume-external stream impingement
L	condition at nozzle lip (exit)
M	model
P	prototype
∞	free stream condition

1. INTRODUCTION

The interaction of rocket or jet plumes with the external flow over a vehicle and surrounding equipment or surfaces is important to the prediction of system performance. In particular, the effects of such interactions are critical to the determination of the base temperature and pressure, afterbody external flow separation, flow field at angle of attack, afterbody fin effectiveness and launch equipment performance.

Rocket or jet plumes have been treated in wind tunnel tests using a variety of methods which include the use of cold air through geometrically modeled nozzles, heated air, small rocket motors, solid surfaces with simulated plume shape (calculated or from tests), and gases other than air. Shortcomings inherent in these simulation methods can be traced to failure to account for all, or part, of such factors as plume elasticity, mass entrainment wake closure, influence of specific heat ratio, viscous effects, and temperature.

It is, of course, impossible to take account of all the contributing parameters simultaneously in a simulation test. While certain methods are more appropriate than others, i.e., cold gas rather than solid surfaces, only limited comparison has been undertaken between results for a simulation model and an actual prototype.

The University of Illinois and the FFA have carried out individually and collectively investigations on simulation problems. A modeling methology using dissimilar propellant gases has been discussed by Korst [1, 2]* and the modeling technique was studied by a limited experimental investigation [3]. It was concluded, that the plume modeling methodology as suggested and developed by Korst [1] showed promising results, but that for a critical evaluation of the merits and limitations of the modeling technique,

---

*Numbers in brackets refer to entries in REFERENCES

further reliable experimental data are urgently needed.

Experiments conducted with cold air jets at Calspan [19] have already demonstrated the importance of correct geometrical plume modeling for subsonic and transonic ($M_\infty \leq 1.25$) plume-slipstream interference effects. In addition, the parametric variation of jet surface Mach number for given plume geometries has shown the anticipated need of satisfying different wake closure conditions. Preliminary analysis of experiments conducted with angles of attack of up to five degrees, for similar test conditions, indicated that the assumption of axisymmetric plume configurations along the separated wake region is valid [6].

It is the purpose of this project to undertake, in close cooperation with the University of Illinois, the evaluation of the modeling techniques. To this end, it is essential that accurate and well controlled test results be available. Thus, the test conditions must be well known in terms of the wind tunnel working conditions and allow for careful control of the modeled propulsive jet, throat sonic condition, nozzle design methodology, local accelerations and Mach number distribution at the nozzle exit plane, and the working fluid.

The project is proposed [4] and granted as a three year program. The first stage to be carried out by the FFA during the first year is the design and construction of a facility for the use of superheated Freon ($\gamma \cong 1.16$) at high pressure to be used for jet simulation and to carry out a wind tunnel research program on jet plume interaction. The actual model nozzle construction and analysis of the results has been accomplished in cooperation with the University of Illinois and has made use of the same basic models reported on previously [5, 6, 7, 8].

A first semi-annual status report [9], covering the activities during the period 1 Jan 1978 - 30 June 1978, has been issued

for internal management use only. Most of the material presented in [9] is however included in this report, which covers the first year activities.

The report will (1) discuss the facility design and construction and its performance map in relation to past testing and modeling schemes and (2) point to areas which are emerging due to detailed analysis as major contributors and problems to appropriate wind tunnel testing using simulated flows for jet interaction studies.

2. ANALYTICAL BACKGROUND OF JET-PLUME SLIPSTREAM INTERACTION MODELING

2.1 Geometrical modeling of plume boundaries

The analysis of axisymmetric centered expansions [10] can form the basis for geometrical jet plume surface modeling [2, 11] and it can be shown that the accuracy attained by such a procedure extends well beyond the range of convergence for the corner expansion itself [11]. The plume expansion derives its initial conditions from the flow approaching the end of the nozzle. Such conditions, however, can be related, locally, to conical source flow which greatly simplifies the modeling effort.

It is thus possible to determine nozzle exit conditions in terms of the Mach number at the nozzle lip and the conical divergence angle at the lip which will geometrically duplicate the jet contour produced by a gas with different specific heat ratio as it expands from a given nozzle under given ambient (adjacent) conditions. One free parameter still remains to be specified - namely, the jet surface Mach number for the model.

2.2 Downstream jet impingement conditions

Selection of the jet surface Mach number for the model is deter-

mined by the dynamic mechanism of plume-slipstream interactions near their confluence and resulting recompression characteristics. The general objectives of plume modeling require that the pressure rise-plume surface deflection must be satisfied. This establishes the conditions

$$\frac{\gamma_M \; M^2_{F_M}}{(M^2_{F_M} - 1)^{\frac{1}{2}}} = \frac{\gamma_P \; M^2_{F_P}}{(M^2_{F_P} - 1)^{\frac{1}{2}}} \tag{1}$$

if weak shock recompression is expected and

$$\frac{2\gamma_M \; M^2_{F_M} - (\gamma_M - 1)}{\gamma_M + 1} = \frac{2\gamma_P \; M^2_{F_P} - (\gamma_P - 1)}{\gamma_P + 1} \tag{2}$$

in case a strong shock interaction can be sustained by the slipstream. Other modeling conditions can be investigated such as those investigated by Sims and Blackwell [12] or that empirically suggested by Herron [13]

$$\left.\frac{M}{\gamma}\right|_P = \left.\frac{M}{\gamma}\right|_M \tag{3}$$

2.3 <u>Special problems for low exit Mach number or short nozzles</u>

If modeling of a higher molecular weight propellant gas by air $\gamma_M > \gamma_P$ is required, relation (1) will generally result in modeling conditions leading to shorter, lower exit Mach number nozzles for the modeling gas.

In such cases, conical flow will not be attained or approached within the nozzle length available and a more realistic design procedure must be adopted to construct a nozzle with the appropriate nozzle exit conditions near the expansion corner. This can be ac-

complished by utilizing transonic flow approximations to generate initial conditions for treating the nozzle flow by the method of characteristics. Special attention must be given to the possible appearance of compression shocks within an axisymmetric nozzle.

Figure 1 illustrates the need for designing the model nozzle for the correct lip Mach number rather than for the theoretical area ratio based on the assumption of ideal conical source flow.

Results of earlier modeling experiments [3] where the effects of nozzle throat curvature have not been corrected should be reexamined and new programs carried out with closer scrutiny as to the throat transonic flow field effects. This indeed may lead to an explanation for the lack of agreement reported in some earlier investigations.

3. ANALYTICAL AND COMPUTER PROGRAM DEVELOPMENTS

3.1 Introduction

The work described in this section of the report is the result of a close cooperation with the group at the University of Illinois headed by professor Korst, which also has contributed to this report.

While facility design, development, component acquisition and construction have been the main objectives during the first year, work has simultaneously progressed on providing analytical capability compatible with known and emerging areas in plume simulation. In particular for difficulties which arise, due to short nozzles (as in using air models for combustion or real gas prototype), appropriate throat conditions for nozzles with small wall radius of curvature-throat radius ratios and inviscid plume cal-

culation for arbitrary nozzle exit conditions have been investigated.

Developments in these areas were aimed primarily at avoiding the difficulties indicated by the work of Korst [11] and others. The effort has resulted in improved computer program capability to treat in a concise manner the nozzle and plume flow fields for prototype and modeled designs. The individual programs are commented on briefly in the following sections.

3.2 Modeling program

The modeling program M040 of Korst [1] for the computation of modeled nozzles and initial plume shape using the method of centered expansion based on a specified prototype is fully operational. For specified modeling conditions at the plume-external stream impingement such as weak or strong shock recompression [11], the program computes the modeled nozzle lip conditions (Mach number and wall angle) and the external plume shape.

3.3 Inviscid plume shape program

The comprehensive external flow-centered jet base pressure program H019 [14] has been modified to allow the specification of any arbitrary nozzle lip characteristic. This option, INØPT = 5, computes the external plume using the method of characteristics from the specified nozzle exit characteristic given. This allows the comparison of plume shapes and their sensitivity to internal nozzle flow field problems such as arise from short nozzles or those with highly curved throats or unusual wall shapes, see Section 3.4.

3.4 Nozzle programs

For nozzle types which may arise due to air modeling of prototype nozzles and construction requirements of wind tunnel models, it is often necessary to utilize small ratios of throat wall curvature to nozzle throat radius. It has long been known [15] that such conditions lead to distortion of the Mach lines in the vicinity of the throat. While such conditions do not present major problems in long nozzles, they may lead to significant distortions in the exit plume Mach number distribution and initial plume shapes for short nozzles [11]. Consequently, a throat subroutine for nozzle computation has been written which utilizes the method of Kliegel [16] for the initial characteristic condition. This method allows calculation with throat radius of curvature to throat radius ratios of less than unity which covers the conditions that may be encountered in modeling tests.

Modifications are under way to incorporate in the base pressure program H019 [14] as a subroutine and new option (INØPT = 6) a method of characteristics program developed at the University of Illinois for calculating internal nozzle (jet) flows with non-uniform exit conditions. This program allows for highly curved throat conditions and the crossing of characteristic lines, both of which must be considered for the accurate description of nozzle exit flows and, consequently, plume shapes for nozzles typical of wind tunnel models.

4. THE TEST FACILITY

4.1 Introduction

The design of the facility has been modified several times since the initial concept was first established [4]. The constraints in terms of flow time required for the tests, the nozzle and jet

surface Mach numbers to be obtained, nozzle size and consequent flow rates, and of course, cost have been major contributing factors.

The selection of the test gas required that it be moderate in cost, essentially non-toxic and have an appropriate ratio of specific heats without serious real gas effects. Various forms of Freon have been used by other investigators [17] and consequently were among the obvious choices. After an examination of the various alternatives, Freon-22 (Fig. 2 is a pressure enthalpy diagram) was selected. Cost and the chemical stability which allows it to be heated to sufficiently high temperatures without chemical breakdown were major factors in its selection. The latter allows the expansion process to proceed to as high a Mach number as 5 without crossing the condensation line while maintaining near perfect gas characteristics, i.e., parallel temperature and enthalpy lines. The ratio of specific heats, γ, is approximately 1.16 to 1.18 which is nearly ideal for simulation of combustion type jet products.

Modeled nozzles and their consequent flow requirements based on the configurations, prototype, used with air in the extensive FFA programs [3,6,7,8] were computed using various modeling procedures such as those discussed in Chapter 2 and its references. Results have been plotted into the flow rate, Mach number, stagnation pressure plane as shown in Figs 3 and 4 Freon-22 and Argon (as representative for a gas of $\gamma = 1.67$). The nozzle configurations in the higher lip Mach number range (greater than approximately 4) require impractically high levels of pressure but, fortunately, are physically unrealistic as models since the nozzle divergence angles are excessive (greater than 40 degrees half angle). For Argon, considered only as a possible future cross check of the modeling procedures, the constraints are appreciably less severe than for Freon-22.

4.2 Facility description

4.2.1 The Freon supply system

The basic system as designed makes use of the high pressure storage of the FFA's hyp-500 facilities and its related compressor system. This equipment allows the storage of 50 m^3 of air at a pressure of 25 Mega Pascal and is utilized in the simulation system as a constant pressure driver for the Freon. Figure 5 is an annotated schematic of the Freon system, the test model, and the high pressure driver. Figure 6 shows an overview of the facility and Figures 7-13 are photographs of the main parts.

The facility can be separated into two parts: the unheated driver section and the heated and insulated section containing the actual test gas. Referring to the schematic (Fig. 5), the unheated pressure vessel 4 * and the heated and insulated part 7 are constructed in a similar manner using vertical arrays of high pressure tubes. The thermodynamic paths followed by the test gas are shown in Fig. 14 and consist of a constant volume heating process from points 0 to 1 and the essentially isentropic expansion through the nozzle from 1 to 2. The system is designed to provide the maximum supply capacity indicated in Fig. 3 with the upper limit determined by choking and the varying pressure line established by the maximum driving pressure and flow rate pressure loss characteristics of the entire system. It can be seen in Fig. 3 that essentially all practical simulation nozzles of interest fall within the operating range.

Further description of the details of the system can be found in the description of the operational procedures Section 4.3.

*) Numbers in circles refer to item-list in Figure 5

4.2.2 Temperature control system

While it has been possible to save the expense of a pressure control system due to the large volume ratio between the air storage and the Freon plant - resulting in a near-constant pressure drive - it has been necessary to incorporate a feed-back control system in the heating process. Although the required accuracy of the temperature control is not too severe, some ± 2 K from set point being tolerable, a simple system without feed-back to a regulator was rejected due to the unsatisfactory safety margins of a simple system. Some type of over-temperature protection is necessary even with such a system justifying the decision to incorporate the unavoidable temperature sensors in a more elaborate temperature control system. There are several integrated temperature-control systems commercially available at low cost. These were judged unsatisfactory in the present application mainly because of poor insulation between sensors and high-tension lines. For this reason a special control system has been developed. This system is described in some detail in the following.

The heating elements are simple heating-tapes spiralled around the lower part of every second tube within the heated tube array, thus allowing convection to develop within the entire array (Figure 10). The principle of operation of the temperature control system is shown on Figure 15. The system uses a solid state relay (TRIAC) to feed electrical power to the heater. The relays are triggered at zero-crossing of the main voltage, thus avoiding HF radiation.

The controller works in a time-proportional mode, the relays are opened and closed once during a fixed time interval determined by the saw-tooth generator. The ratio between on-time and off-time constitutes the proportional constant in the control system.

Temperature is sensed by an iron-constantan thermocouple. The temperature-proportional voltage is amplified 200 times before being applied to the summing point. The set point voltage, properly compensated for the cold-junction temperature is subtracted from the amplified temperature-proportional voltage. After amplification the error voltage is low-pass filtered and fed to a comparator together with the triangular wave. The repetition time of this wave is 7 s, very much less than the time constants of the heater. This procedure creates the time-proportional sequence.

The thermocouples are positioned as close as possible to the heating tapes, resulting in negligible time-delay or overshoot.

To increase noise immunity, a Schmitt trigger is incorporated in the comparator, the solid-state relay being triggered by a clean square wave.

A complete schematic of the control system is shown in Figures 16 and 17. The numbers within the amplifier symbols correspond to the functional diagram. Two operational amplifiers are contained within the same capsule, hence the repeated numbering.

Not shown is a power shut-down facility activated by a preset (340^{o}C) temperature-controlled switch.

The control system in itself, however, ensures a high degree of over-temperature protection. Within the heated tube array, a total of 4 separate systems is employed. Should one fail and generate full power to one heating element, the others will shut down the power to the rest of the elements when the temperature increases above set point.

4.3 Operational procedures

4.3.1 Charging the system

The basic operating procedure is as follows: Prior to the run, the system is charged by the charging pump (14) to the state where the heated portion contains the correct amount of Freon to reach the desired pressure and temperature after being heated at constant volume. This is process 0-1 shown in Fig. 14 and the required volume is approximately 0.25 m^3. The determination of the amount of Freon charged is facilitated by use of a pump revolution counter for metering purpose. The pump is of diaphragm type and should normally operate with Freon in the liquid state.

The valve (5) is then closed and charging is continued until the unheated portion of the system has reached the pressure prescribed for the run (state 1 in Fig. 14). Small pressure corrections may be necessary and these can be made using the needle valve (6), discharge line (3), or charging pump (14) as appropriate.

4.3.2 Heating process

The heating process is accomplished by heating only a portion of the tubes, thus producing thermal circulation within the high temperature tube array as described in Section 4.2.2. The convection persists until the desired temperature is reached. During the heating period, the gas line feeding the nozzle is preheated by allowing a small amount of air to flow from tube (16) through heater (17) and out through the nozzle. At the end of the heating cycle, the pressures are ideally equal, i.e. the hot and cold parts of the system should have the same pressure as the high pressure storage and line (1).

4.3.3 Running operations

A run is initiated by first opening valves (2) and (5). Since the pressures are equalized little or no gas will flow. The preheating air flow (16) is then closed off and the control valve (11) is rapidly opened. The hot gas is now driven at essentially constant pressure from the air line and 50 m^3 of storage. The relative size of the high pressure storage to system volume, about 200 to 1, produces a small but negligible pressure drop during a typical 15 second run.

The cold Freon serves as a cushion between the air and test gas to prevent mixing of the driver air and hot test gas. The density relations between the cold Freon cushion and hot gas are such that no thermal convection occurs at the interfaces.

An individual run may last as long as the gas temperature is constant and the system design is for 15 second test times. A small portion of the cold Freon will be sufficiently heated from entering and traversing the warm tube array to also serve as test gas and thus allowing slightly increased run times over the nominal design value.

The run is terminated by closing the control valve (11). Valve (2) is then closed and the air in the cold tubes is discharged to the atmosphere through valve (3). The Freon in the system expands during the discharge process of the air and can be detected when it reaches the discharge valve (3) at which time the valve is closed. This process saves Freon.

Upon completion of the discharge process, the pressure within the system is close to, or slightly below, the correct (depending upon the desired run pressure) initial charge pressure for the hot part of the system. This also results in a reduction of lost or wasted Freon.

4.4 Status of the facility construction, 31 Dec 1978

The on-site assembly of the facility started at the end of September 1978 and the high pressure system was ready for the mandatory pressurizing tests with water the first week in November. While the manufacturing and assembly of the facility so far had proceeded without unforseen difficulties, a rather special problem showed up after the water pressurizing tests. According to specifications, the tubes should have been thoroughly cleaned after welding. This was accomplished by sand blasting. Traces of sand obviously had been left within the tubes. During the water pressurizing tests rust inhibitors were added to the water. Contrary to what was claimed by the contractor, the inhibitors did not evaporate together with the water, resulting in fairly large quantities of greasy sand sticking to the internal walls of the tubes.

Cleaning was accomplished in steps with disconnected parts of the facility by subsequent blow-downs using high-pressure air as propellant. Several hundred blow-downs were necessary to clean the system. As the cleaning had to be coordinated with the regular wind tunnel operations using the same high pressure air facility, this process was very time consuming, and delayed the construction about one month.

In December the electrical installation of the heating system and the thermal insulation were accomplished. Some shake-down heating tests with high pressure air in the system were carried out to check the heating system before insulation was applied. The results of the tests indicated that the heating arrangement performed as predicted.

5. WIND TUNNEL MODEL

5.1 Model modifications

In order to meet the acquired physical properties of the Freon in the stagnation chamber of the model (pressure and temperature) some modifications had to be done to the model and the installation. The modifications shown in Figures 18-21 include the following changes

a. Two insulated tubes for supplying the Freon to the stagnation chamber of the model are provided. The new tubes have appreciably increased cross sectional area and smooth curvature to decrease the pressure drop at large mass flows. The insulation is important to minimize the heat losses. The old tubes are used to supply the necessary cooling medium (air or Freon) for the hull of the model and the internally mounted Scanivalve. A trailing edge fairing covers the supply tubes. The fairing has the dual purpose of decreasing the heat losses and minimizing the strut wake.

b. A new inlet to the stagnation chamber which will give lower pressure losses, and better velocity distribution.

c. A temperature probe with a thermo-couple is installed in the stagnation chamber to measure the Freon total temperature.

d. The front part of the cylindrical model portion is lengthened by half a diameter to provide space for a larger drive motor and a gear box for the Scanivalve. The smaller Scanivalve drive used hitherto in this model has in some cases been unreliable. The gear-box has been specially designed for this application and is being manufactured. Another advantage with moving the

Scanivalve is that it is situated farther from the hot part of the model and the risk for temperature drift of the pressure transducer is smaller. If transducer temperature drift should turn out to be a problem, there is also the possibility to use Scanivalves outside the wind tunnel, but this will demand longer running time.

e. In the earlier tests the strut was situated below the model, as shown in Fig. 18. The strut arrangement has been changed so that the strut is now situated above the model as in Figs 19-21. This arrangement gives for the Freon tests shorter piping with fewer bends and hence lower pressure losses.

5.2 Test nozzles

5.2.1 Introduction

The operational capability of the plume modeling facility as a function of nozzle mass flow, stagnation pressure and lip Mach number has been described previously [18] and is also discussed in other sections of this report. Modeling of the extensive FFA air test data for two specific nozzles [9] using both strong and weak shock closure conditions [18], as shown in Fig. 3, indicated that while the facility covers most of the nozzle performance range, the weak shock tests are limited to pressure ratios of approximately 6 or less. Since the initial nozzle tests should allow for testing both weak and strong shock modeling, see Chapter 1, as well as operation at off-design conditions, see Fig. 1, additional nozzle configurations have been investigated.

5.2.2 ZAP nozzle

A nozzle design called ZAP-nozzle suggested as a suitable con-

figuration for wind tunnel tests was received from the University of Illinois based on information transmitted by MIRADCOM*. This nozzle, Fig. 23, which exhibits a double conical profile in the expansion section was constructed at FFA and shipped to the University of Illinois for calibration and analysis.

It was later discovered that the actual nozzle used in full scale sled tests** did not have the expansion section wall discontinuity. However, since effort had been expended in the theoretical analysis of non-constant (wall discontinuity) nozzle wall, it was deemed desirable to proceed with experimental verification of the original nozzle design. The predicted internal flow was found to be in excellent agreement with the experimental results.

This nozzle will be modified to the actual sled test configuration and recalibrated at the University of Illinois before being returned to the FFA.

5.2.3 Nozzle for initial calibration tests - modeling Freon to Air

The existing $M_L = 2.5$, $\theta_L = 10^\circ$ and 20° nozzles used extensively in earlier test programs were rebuilt to fit into the slightly modified model, Figure 25, and will be used as calibration nozzles for air and Freon. This will allow to model Freon to air (combustion gas simulation to air) in contrast to the previous air to Freon studies.

5.2.4 Nozzles for initial modeling tests - Air to Freon

A comparison of three air nozzles reported on by the FFA [8], i.e. M_L (nominal) = 2.5, $\theta_L = 0^\circ$, 10° and 20°, for weak and

*MIRADCOM denotes Missile Research and Development Command

**ZAP plume study sled test conducted at Holloman Air Force Base, high speed track, 1977 - report pending

strong shock modeling are shown in Figs 3 and 24 along with the facility performance (note that the three nozzles also are respectively shorter - 0^{o} through 20^{o} - leading to increased effects of non-uniform exit conditions). From Fig. 24 it is seen that the 10^{o} nozzle allows the greatest initial potential for studying the various modeling closure conditions and for operating at off-design conditions. Thus, the initial models being constructed are modeled against the $M_L = 2.5$, $\theta_L = 10$ air prototype for:

(a) For a pressure ratio of 6:1 (with air) and weak shock modeling
R_C/R^* (radius of wall in throat to radius of throat) = 3.0
$\theta_L = 19.76^{o}$ (this gives $M_L = 3.90$)
$R^* = 2.510$ mm (based on $R_e = 15.0$ mm)
$P_o|_{\text{nominal test condition}} = 128.63$ BAR (based on P_o of S4/S5 = 1 BAR).

(b) For a pressure ratio of 9.2 (with air) and strong shock modeling
$R_C/R^* = 3.0$
$\theta_L = 14.19^{o}$ ($M_L = 3.192$)
$R^* = 4.55$ mm ($R_e = 15$ mm)
$P_o|_{\text{test}} = 56.86$ BAR (nominal test condition).

The nozzles are shown in Figure 26.

6. PLANNED PROGRAM FOR INITIAL TESTS

6.1 Calibration tests

The two rebuilt nozzles for $M_L = 2.5$; $\theta_L = 10^{o}$ and 20^{o}, described in Section 5.2.3 will be tested primarily with air for comparison with earlier test results. The tests will be made at $M_\infty = 2.0$ and zero angle of attack with variation of the jet pressure ratio P_L/P_E. The pressure distribution on an 8^{o} conical boat-tail of length one diameter will be determined and Schlieren photographs taken.

The test results will show if there are any effects of the model and strut modifications. The thickness of the boundary layer at the strut of the boat-tail will be measured to check the influence of the lengthened fore-body.

A corresponding series of tests with Freon will follow after the air tests.

6.2 Modeling tests

The two nozzles for $M_L = 3.90$ and 3.19, described in Section 5.2.4 will be tested with Freon at $M_\infty = 2.0$ and zero angle of attack. The jet pressure ratio P_L/P_E will be varied and the Freon temperature will be kept high enough to avoid condensation in the fully expanded plume. The pressure distribution on a 8^o conical boat-tail of length one diameter will be measured and Schlieren photographs taken. Oil flow pictures of the surface flow on the boat-tail will be taken for a few selected cases.

7. CLOSURE

A three year program for investigation of plume-afterbody flow interactions to obtain data, such that critical evaluation of the merits and limitations of plume modeling techniques can be accomplished, has been undertaken by the FFA in close cooperation with the University of Illinois. During the first year, which this report covers, the following preparations for the experimental investigation and computer program developments have been carried out.

1. Design and construction of a facility for superheated Freon of high pressure to be used for jet plume simulation have been accomplished. Test runs will be possible

with Freon 22 for 10-15 seconds. Stagnation pressures up to 20 Mega Pascal and stagnation temperatures up to 550 K can be used. Shake-down testing of the facility has started.

2. The strut supported, sting mounted axi-symmetric model, extensively used in previous plume-afterbody flow investigations, has been modified for tests with heated Freon.

3. Two model propulsion nozzles for calibration tests and three nozzles for modeling tests have been constructed. The selection of nozzle configurations and the actual nozzle construction have been accomplished in cooperation with the University of Illinois. One of the nozzles, the so-called ZAP-nozzle was shipped to the University of Illinois for calibration and analysis. The predicted internal flow was found to be in excellent agreement with the experimental results.

4. The computer program capability has been improved to treat in a concise manner the nozzle and plume flow fields for prototype and modeled designs.

REFERENCES

1. Korst, H.H. Approximate Determination of Jet Contours near the Exit of Axially Symmetrical Nozzles as a Basis for Plume Modeling. TR-RD-72-14, August 1972, US Army Missile Command, Redstone Arsenal, Ala.

2. Korst, H.H. An Analysis of Jet Plume Modeling by Dissimilar Propellant Gases. Proc., 43rd Semi-Annual Meeting, Supersonic Tunnel Association, 2-3 April 1975, Pasadena, Cal.

3. White, R.A.; Korst, H.H.; Agrell, J. — Preliminary Experimental Evaluation of Theoretical Modeling Concepts for Plume Slipstream Interactions. Proc., 45th Semi-Annual Meeting, Supersonic Tunnel Association, 13-14 April 1976, Albuquerque, New Mexico.

4. Nyberg, S.-E. — Investigation of Modeling Concepts for Plume-Afterbody Flow Interactions. Research proposal FFAA-77-4 to US Army European Research Office, June 1977.

5. Agrell, J.; Gudmundson, S. E. — A Review of the Experimental Technique used at the FFA in the Study of the Jet Effects on Afterbodies in Transonic and Supersonic Wind Tunnels and Some Results from the Investigations. FFAP-A-370, paper presented at Sitzung des DGLR-Fachausschusses, "Versuchswesen der Fluid- und Thermodynamik", 1976, at Technische Universität, Berlin, West-Germany.

6. White, R.A.; Agrell, J. — Boattail and Base Pressure Prediction including Flow Separation for Afterbodies with a Centered Propulsive Jet and Supersonic External Flow at Small Angles of Attack. AIAA Paper 77-958, also, Proc., AIAA/SAE 13th Propulsion Conf., Orlando, Florida, 11-13 July, 1977.

7. White, R.A.; Addy, A.L.; Agrell, J. — An Improved Experimental and Theoretical Base Pressure Correlation for Conical and Cylindrical Afterbodies with Centered Propulsive Jet. Proc., 10th Int. Symp. on Space Tech. and Sciences, Tokyo, Japan, September 1973.

8. Agrell, J.; White, R.A. — An Experimental Investigation of Supersonic Axisymmetric Flow over Boattails with Centered Propulsive Jet. The Aeronautical Research Institute of Sweden (FFA), Tech. Note AU-913, Dec 1974.

9. Nyberg, S.-E. — Investigation of Modeling Concepts for Plume-Afterbody Flow Interaction. Grant DAERO-78-G-D28, 1st Semi-Annual Status Report, 1 Jan 1978 - 30 June 1978. Internal report for ERO and FFA.

10. Johannesen, N.H.; Meyer, R.E. — Axially-Symmetrical Supersonic Flow Near the Centre of an Expansion. The Aero. Quart., Vol 2, 1950, pp 127-142.

11. Korst, H.H. — Analytical concepts for modeling of propulsive jet plume interference effects. Proc., 1st Int. Conf. on Mathematical Modeling, St. Louis, Mo., 29 August to 1 September 1977 (with Addendum); also UILU ENG 77-4010, University of Illinois, Department of Mech. and Ind. Engr., Gas Dynamics Laboratory, Urbana, Ill., 1977.

12. Sims, J.L.; Blackwell, K.L. — Base pressure correlation parameters. Paper presented at the Workshop on Missile and Plume Interaction Flow Fields, Redstone Arsenal, Ala., 7-8 June, 1977.

13. Herron, R.D. — Investigation of the jet boundary simulation parameters for underexpanded jets in quiescent atmosphere. AEDC-TR-65 Arnold Engr., Development Center, Tullahoma, Tenn., September 1968.

14. Addy, A.L. — Analysis of the axisymmetric base-pressure and base temperature problem with supersonic interacting freestream-nozzle flows based on the flow model of Korst, et al. Part III: A computer program and representative results for cylindrical, boattailed, or flared afterbodies. U.S. Army Missile Command, Report No. RD-TR-69-14, February 1970.

15. Oswatitsch, K.; Rothstein, W. — Flow pattern in a converging-diverging nozzle. TM 1215, UACA, March 1949.

16. Kliegel, J.R.; Levine, J.N. — Transonic flow in small throat radius of curvature nozzles. AIAA Journal, July 1969, Vol. 7, No. 7, pp. 1375-1378.

17. Henson, V.K.; Sims, J.L.; Blackwell, K.R. — Preliminary Report, Northrop Services, Inc.: Mr. V.K. Henson, Technical Monitor (NASA); Mr. J.L. Sims (S&E-AERO-AF); and Mr. K.R. Blackwell (S&E-AERO-AAE). Preliminary Report prepared for the Aero-Astrodynamics Laboratory of Marshall Space Flight Center under Contract No. NAS8-21810, report No. TN-230-1267.

18. White, R.A.; Nyberg, S.-E.; Korst, H.H.; Hevreng, T.; Agrell, J. — Development of a plume modeling facility and test methology. Proc. 49th Semi-Annual Meeting, Supersonic Tunnel Association, April 17 and 18, 1978.

19. Direct communication of test results through Mr. Charles E. Reed of Calspan and Mr. James Henderson at MIRADCOM, Huntsville, Ala.

ACKNOWLEDGEMENT

The authors wish to thank Professor H.H. Korst and Professor R.A. White at the University of Illinois for helpful cooperation and for their contributions to this report.

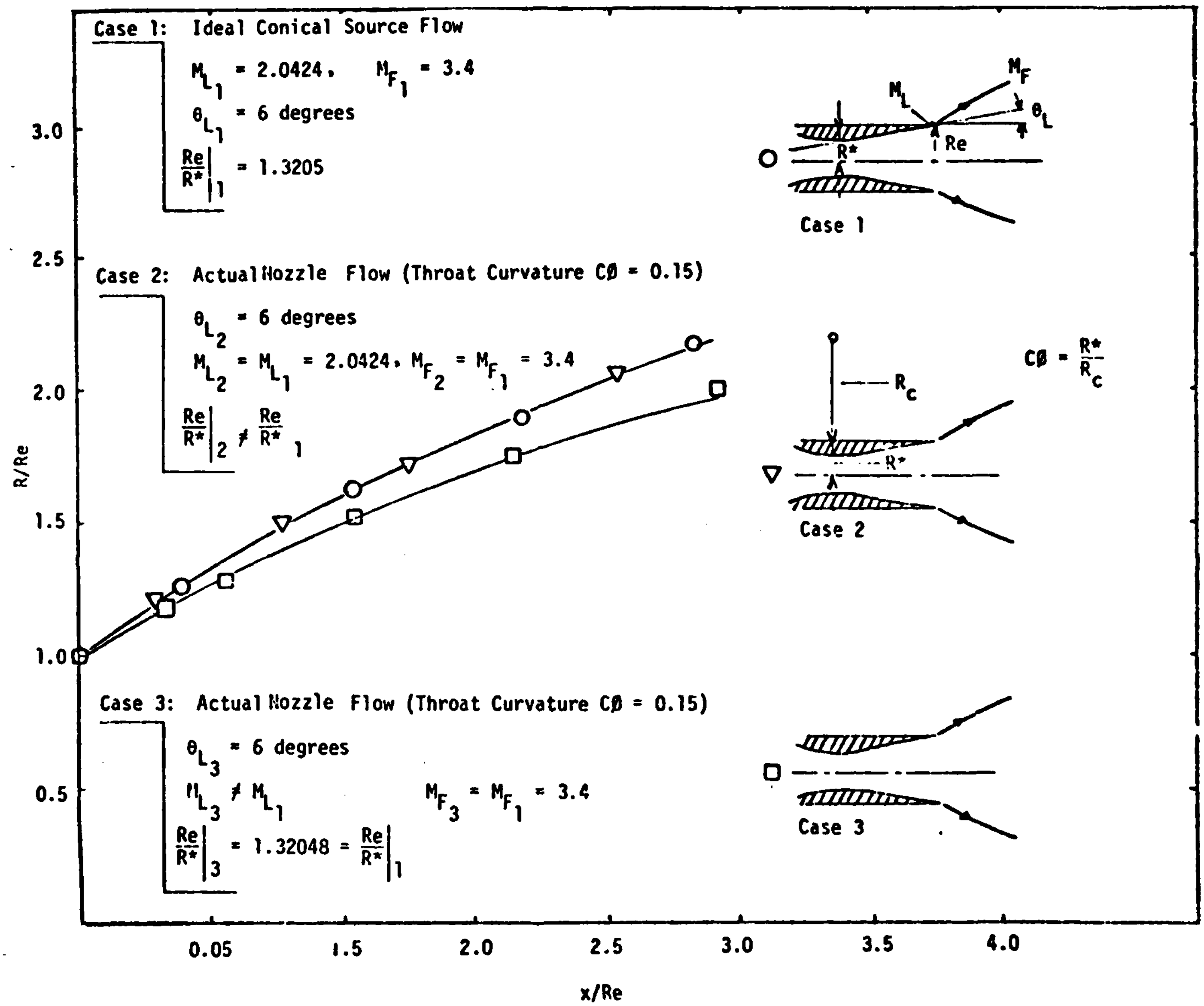


Figure 1. Effects of throat sonic conditions and internal flow analysis on plume shape. [18]

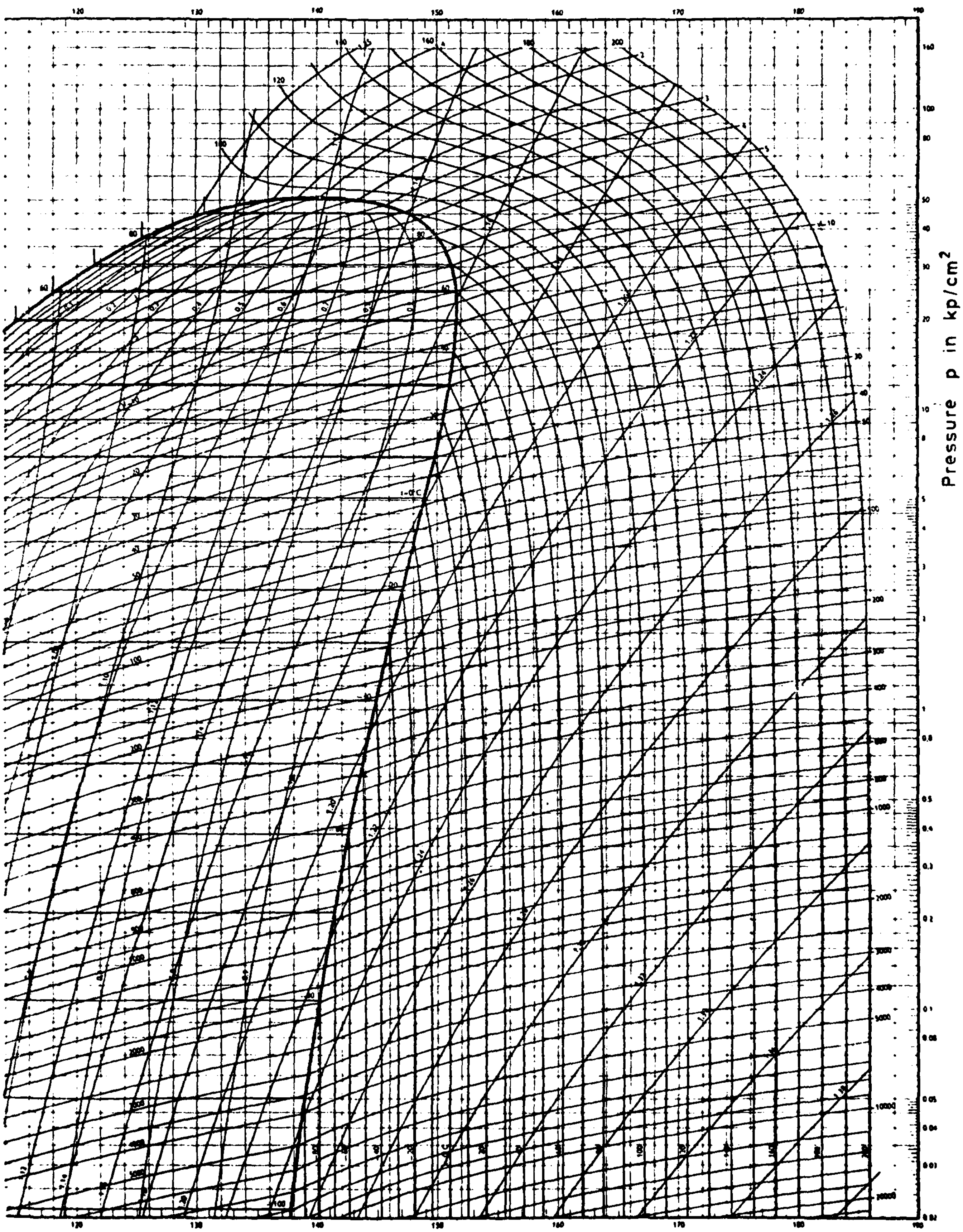


Figure 2. Enthalpy-pressure diagram for Freon 22.

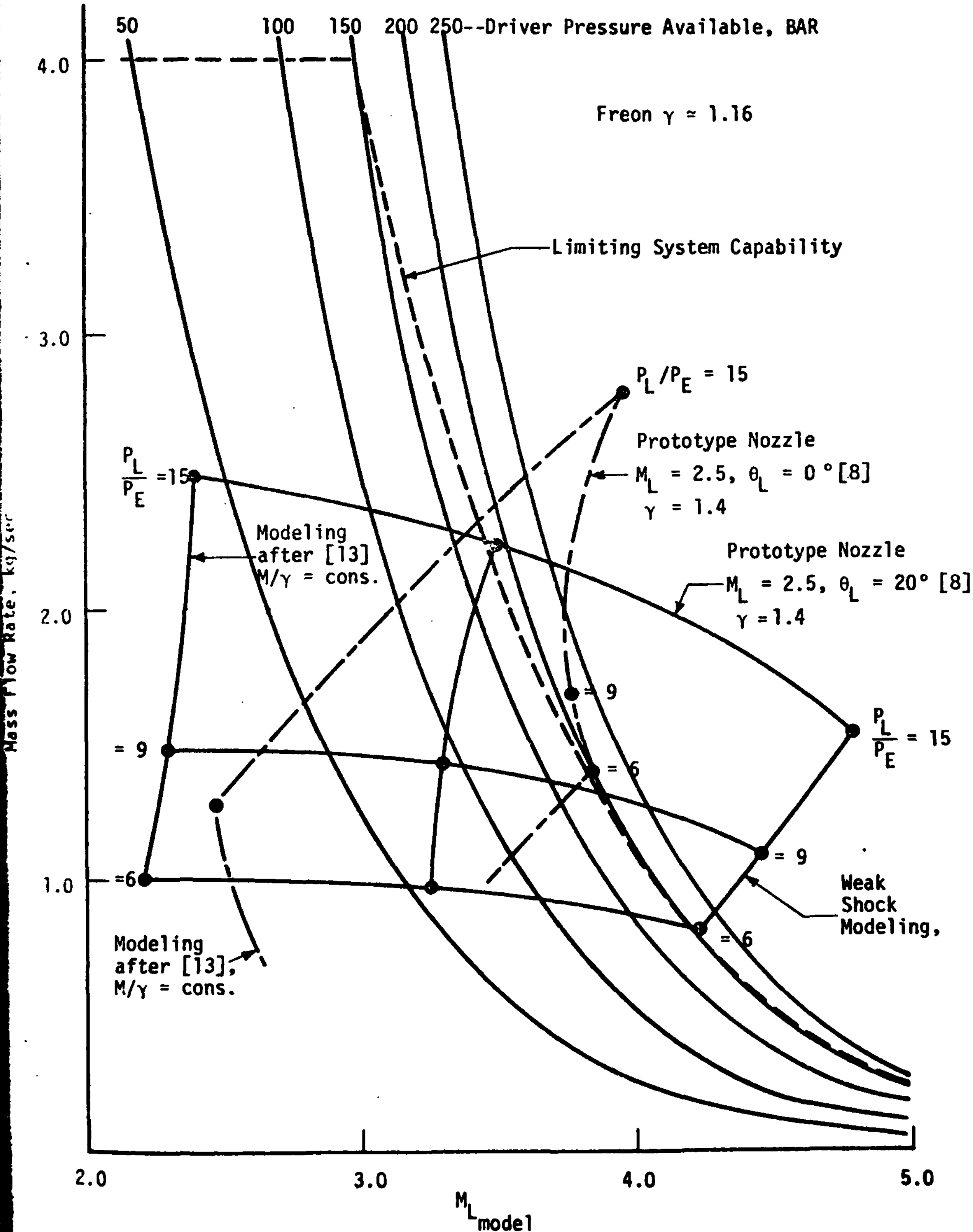


Figure 3. System performance with Freon and model map for two prototype nozzle configurations [8].

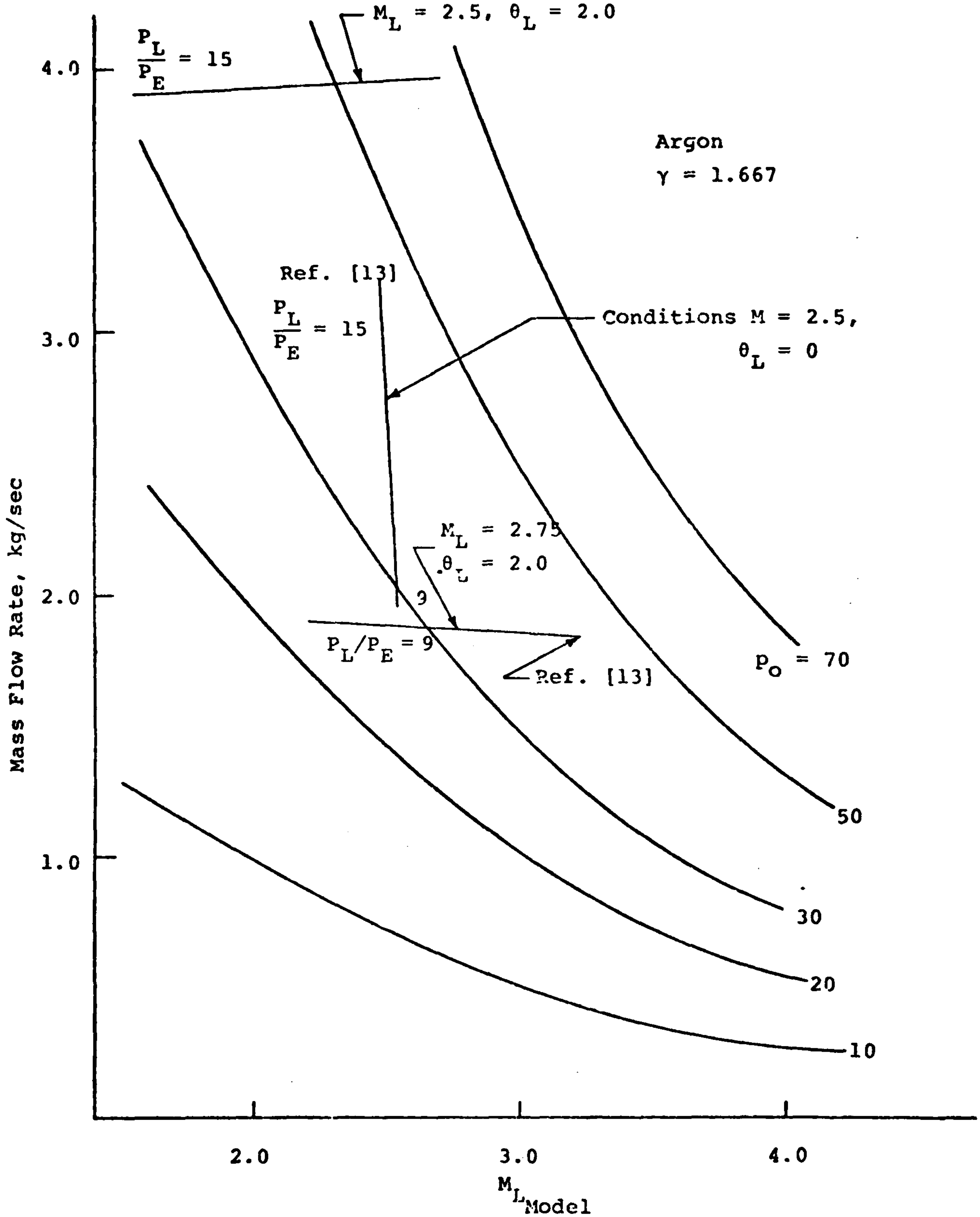
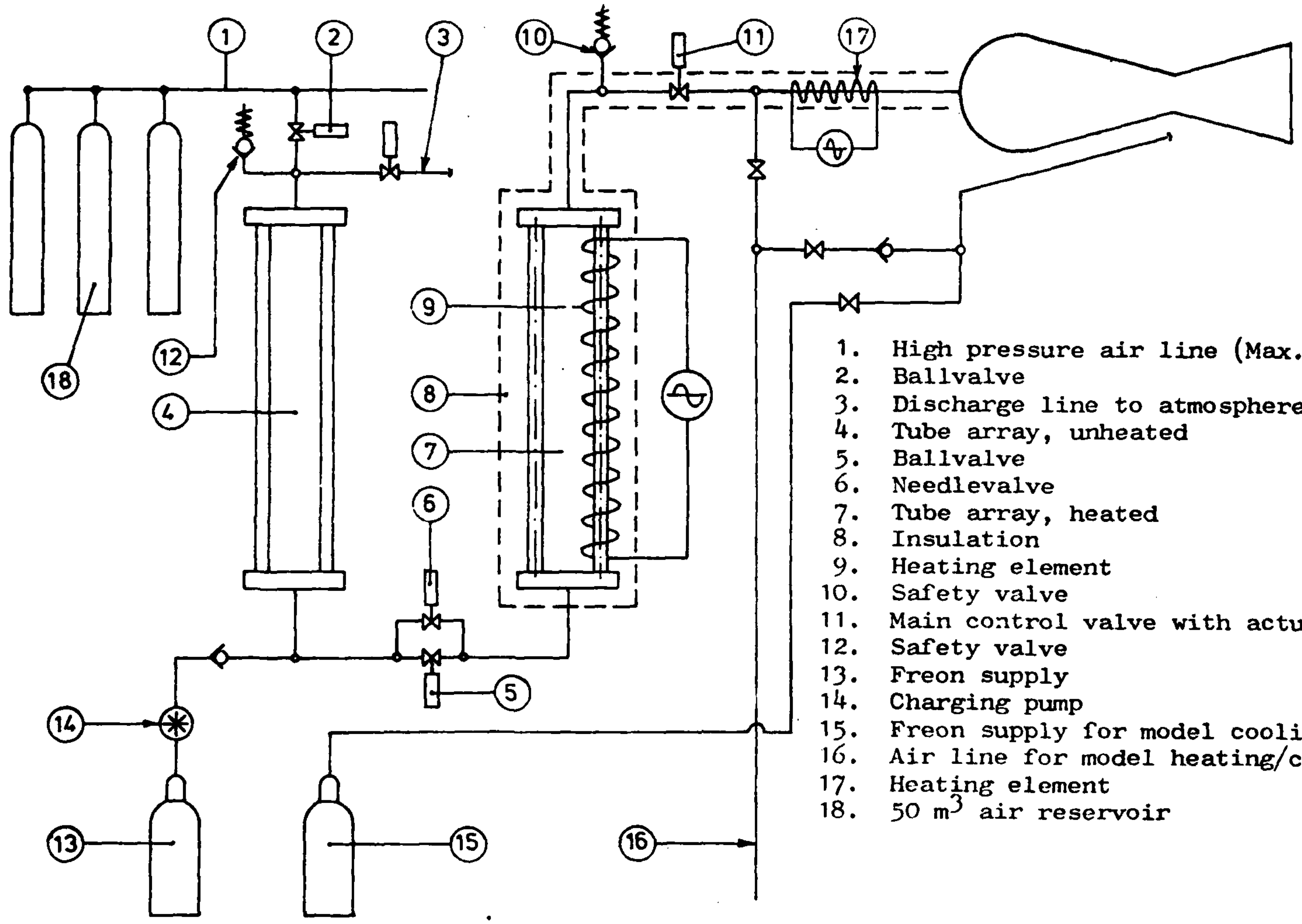


Figure 4. System capability with Argon and model conditions for three prototype nozzle configurations.



1. High pressure air line (Max. 25 MPa)
2. Ballvalve
3. Discharge line to atmosphere
4. Tube array, unheated
5. Ballvalve
6. Needlevalve
7. Tube array, heated
8. Insulation
9. Heating element
10. Safety valve
11. Main control valve with actuator
12. Safety valve
13. Freon supply
14. Charging pump
15. Freon supply for model cooling system
16. Air line for model heating/cooling system
17. Heating element
18. 50 m^3 air reservoir

Figure 5. *Annotated schematic of air driver system, Freon heater and nozzle.*

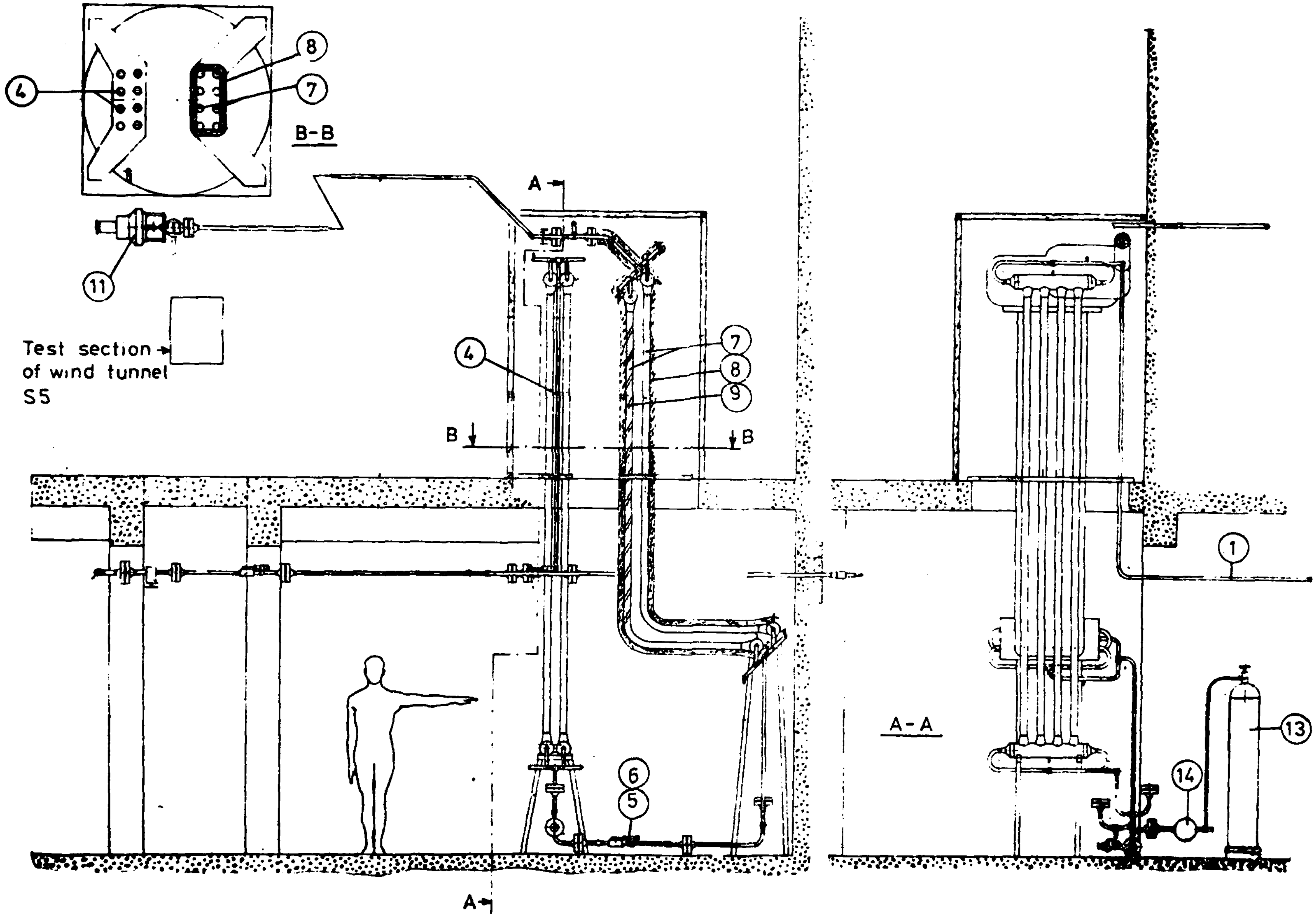


Figure 6. Freon supply facility. Numbers in circles refer to item list in Figure 5.

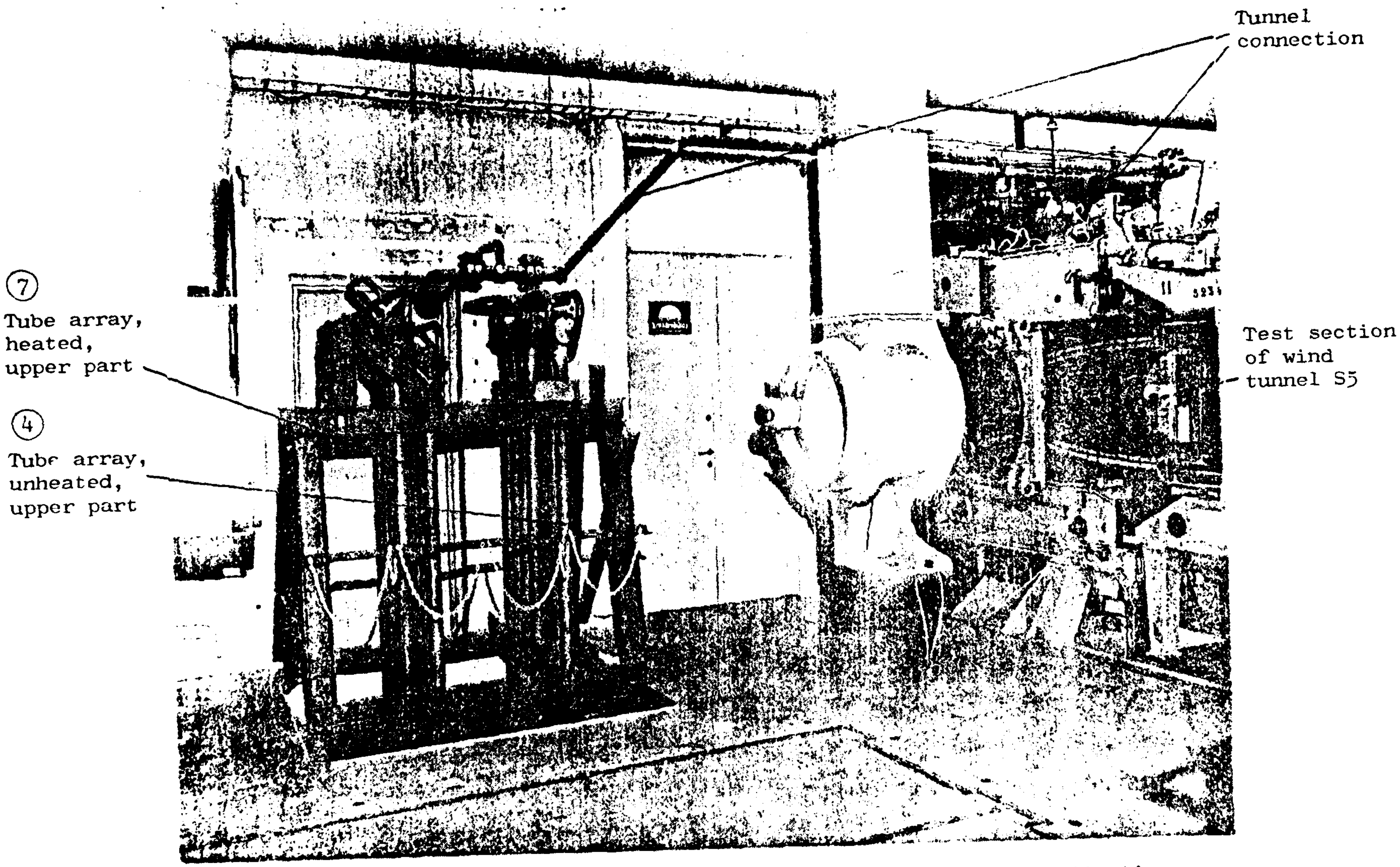


Figure 7. Tube arrays, upper part, and tunnel connection before application of insulation. Numbers in circles refer to item list in Figure 5.

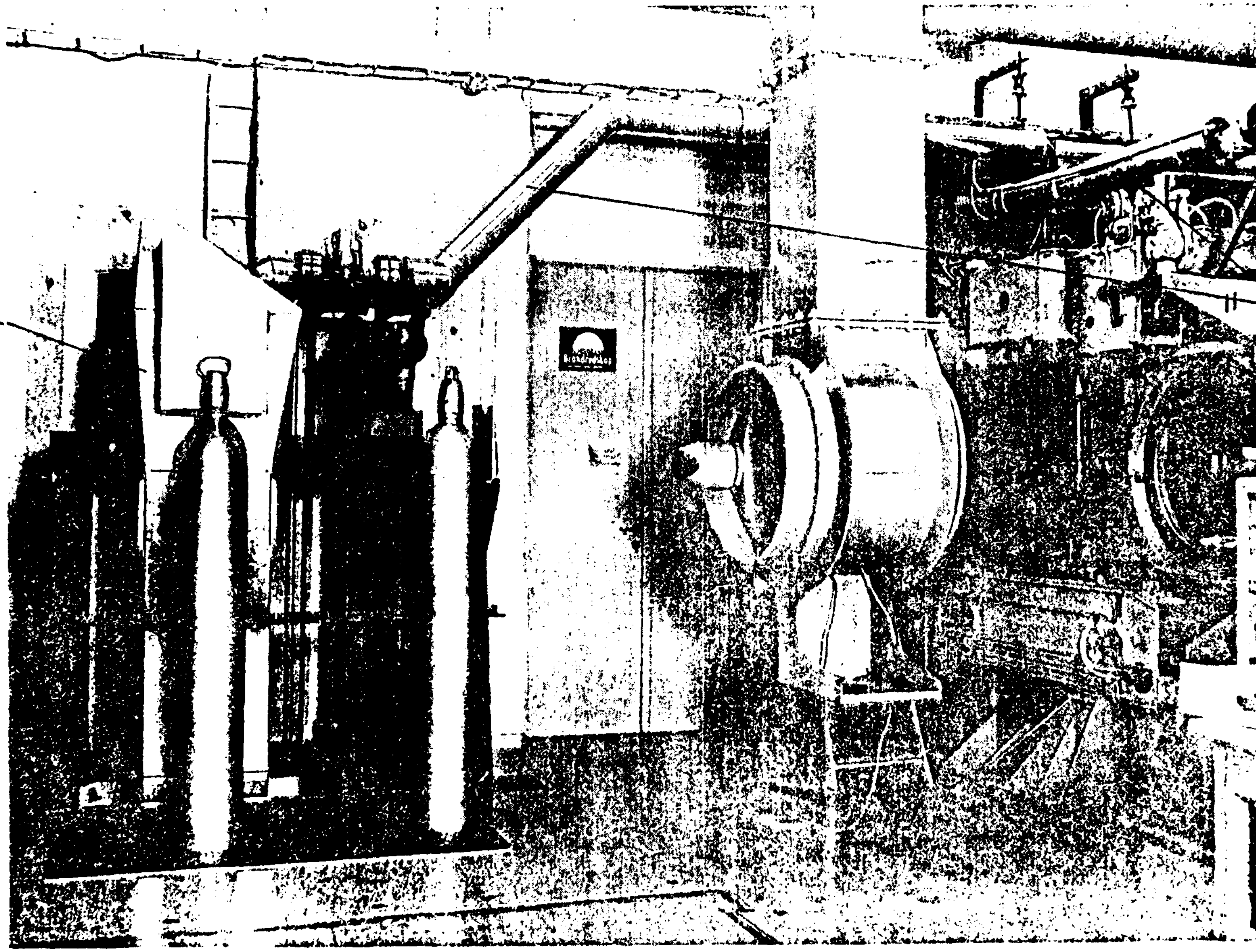


Figure 8. Tube arrays, upper part, and tunnel connection with insulation applied. Numbers in circles refer to item list in Figure 5.

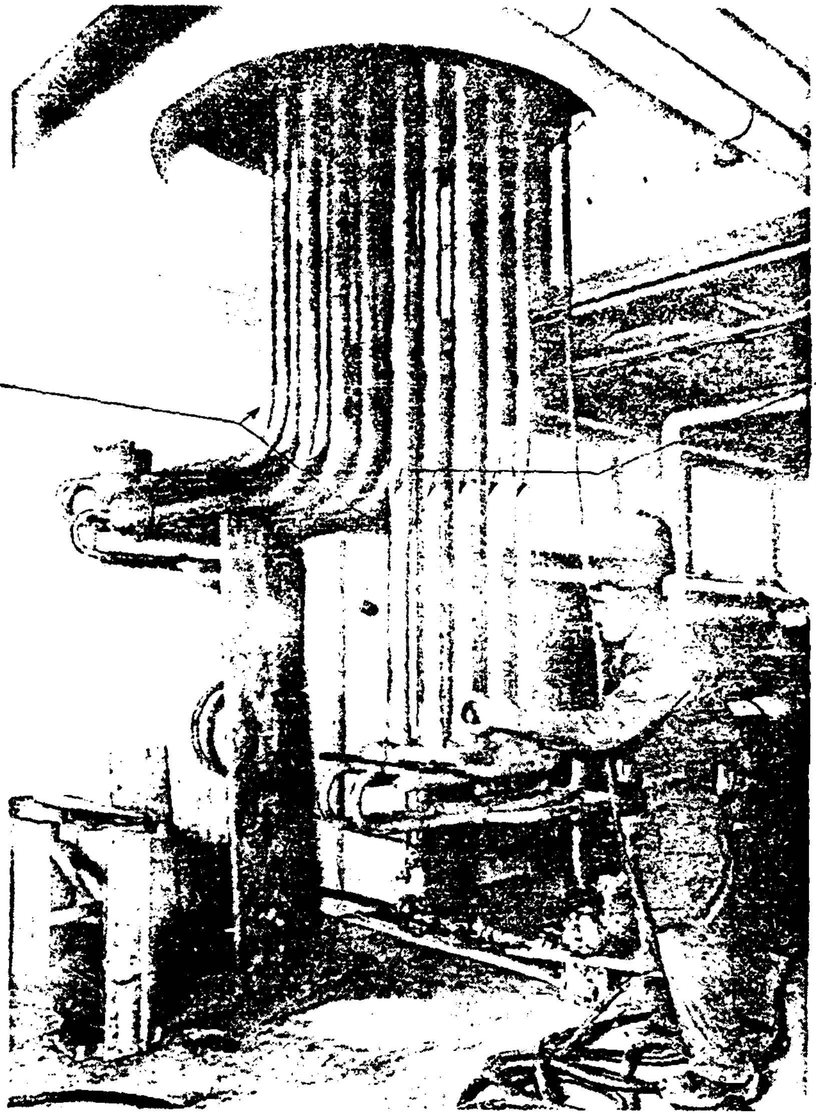


Figure 9. Tube arrays, lower part, before application of heating elements and insulation. Numbers in circles refer to item list in Figure 5.

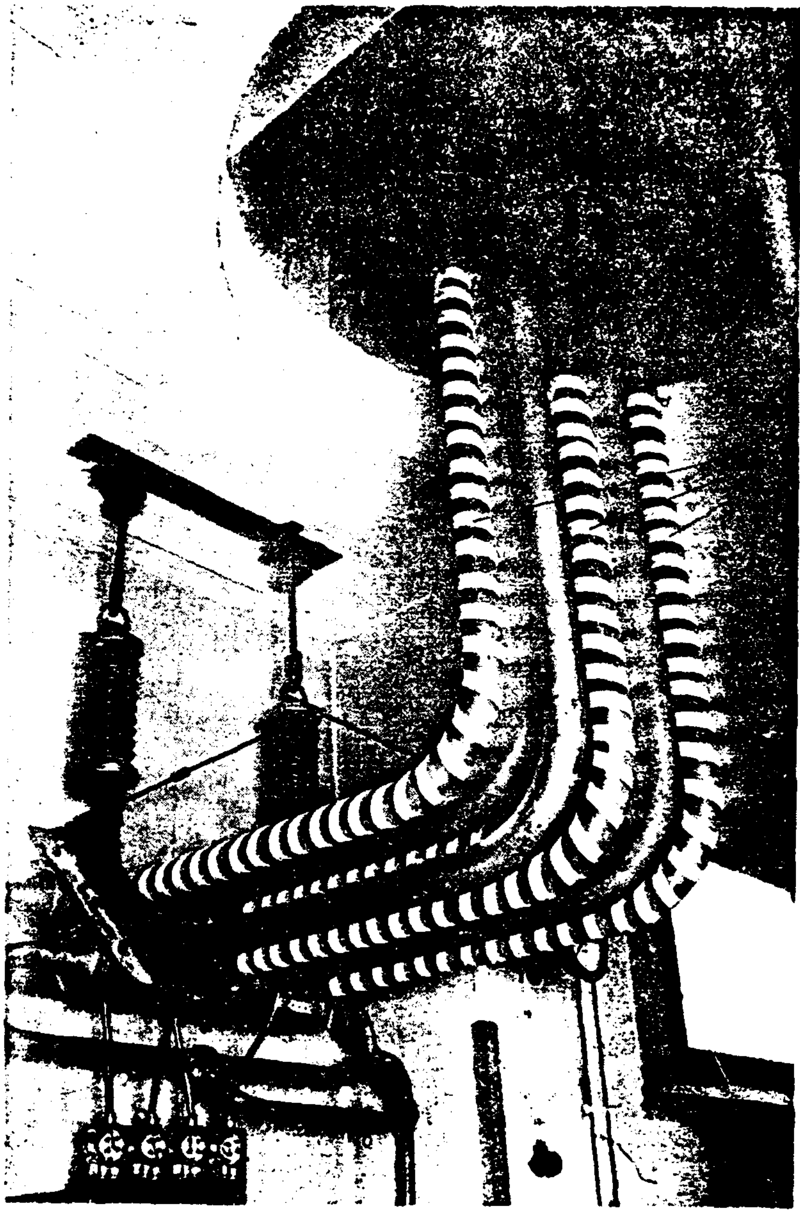


Figure 10. Heated tube array, lower part, with heating elements applied but without insulation.
Numbers in circles refer to item list in Figure 5.

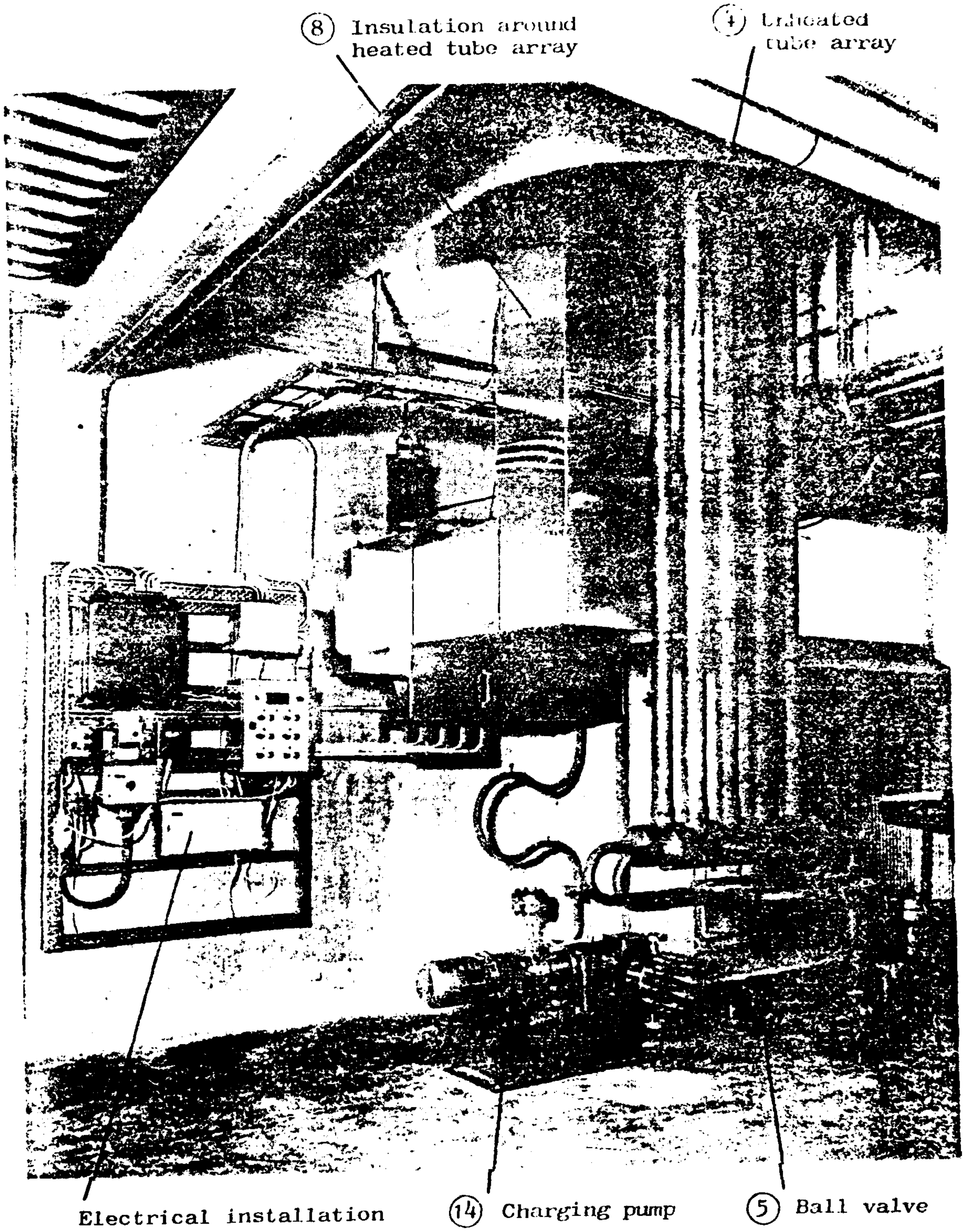


Figure 11. View of the Freon supply facility. Numbers in circles refer to item list in Figure 5.

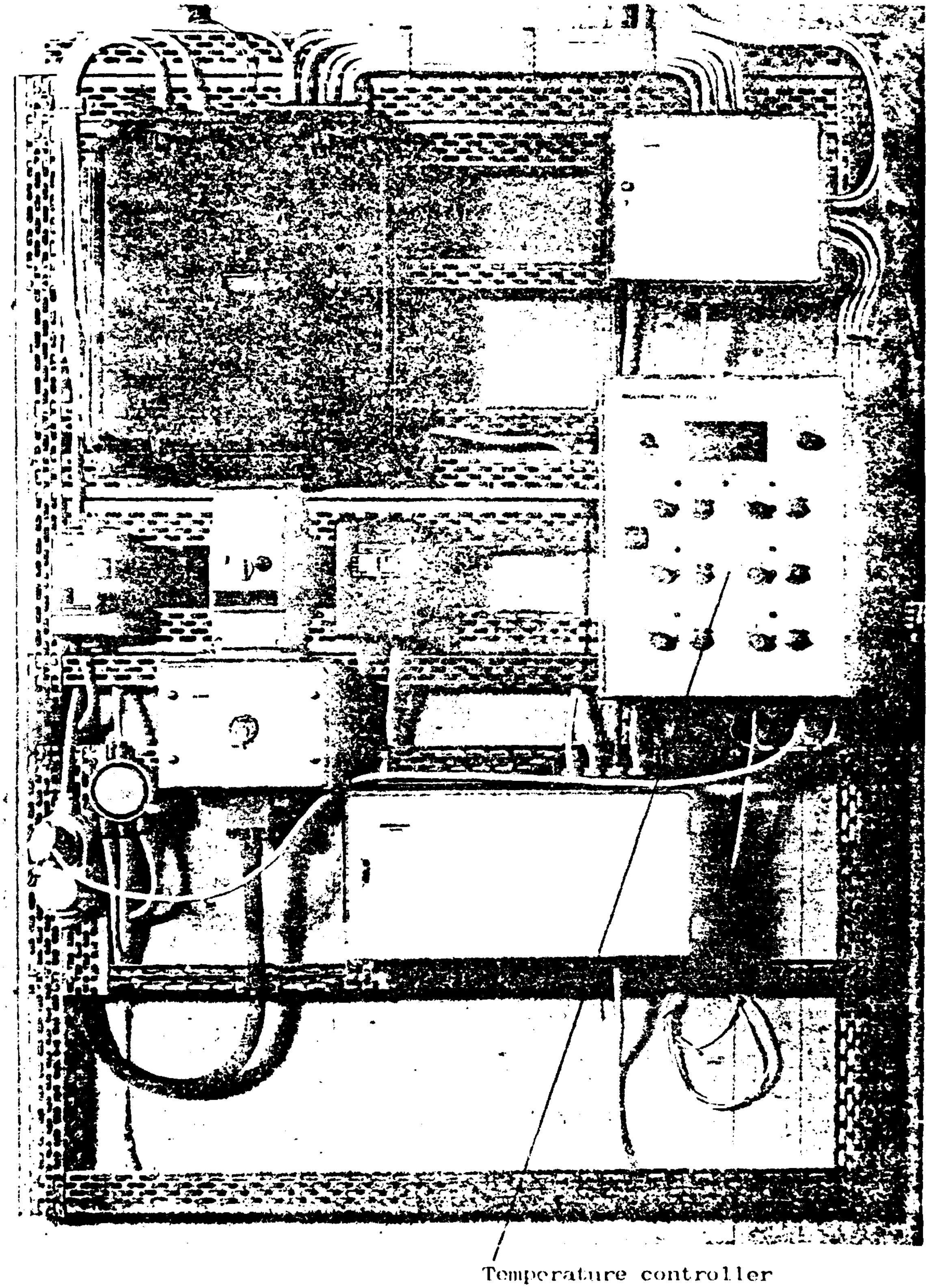


Figure 12. Electrical installation for Freon supply facility.

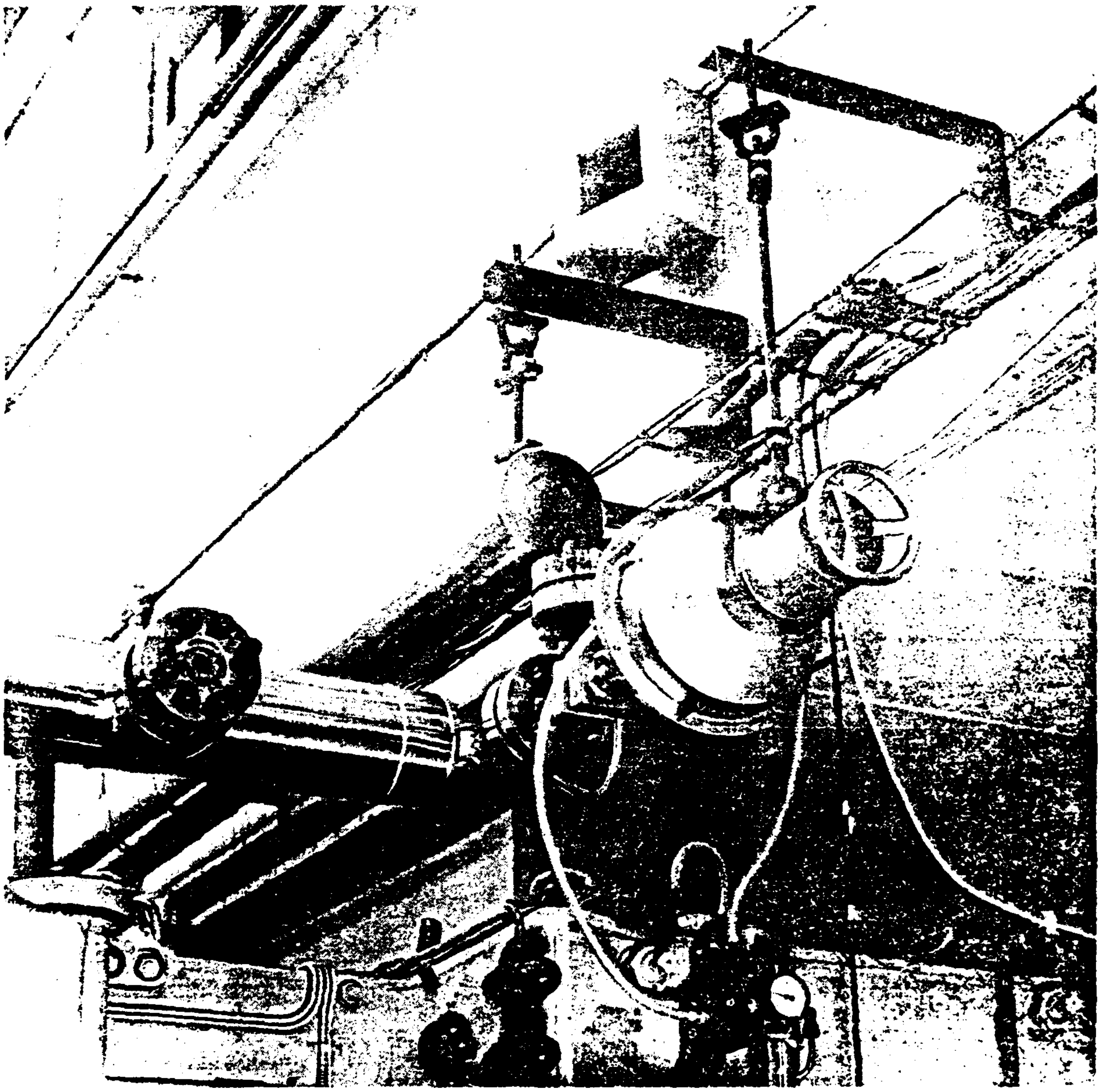


Figure 13. Fast acting main control valve.
(item 11 in Figure 5)

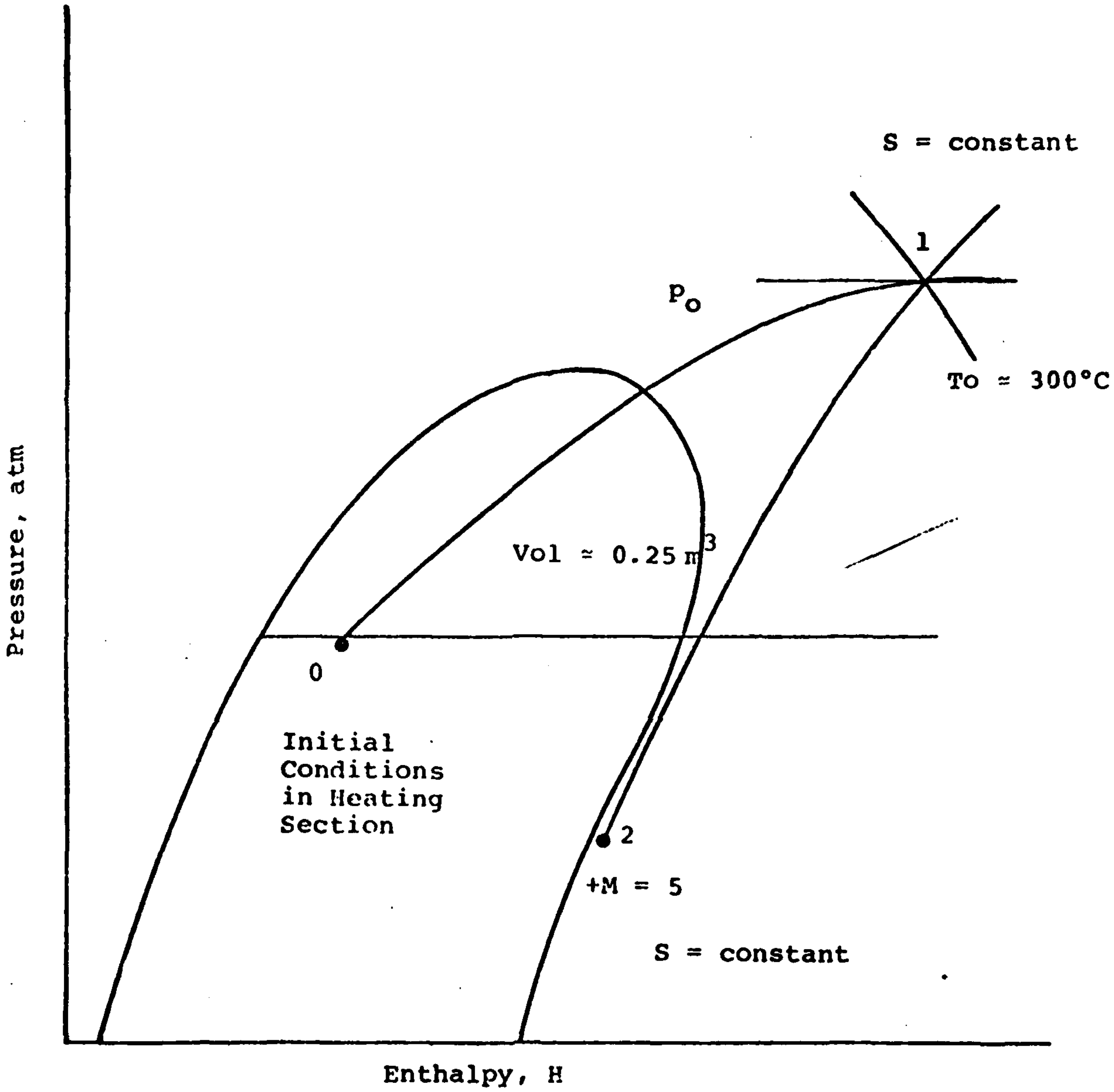


Figure 14. Schematic of thermodynamic paths for the Freon heater and nozzle expansion.

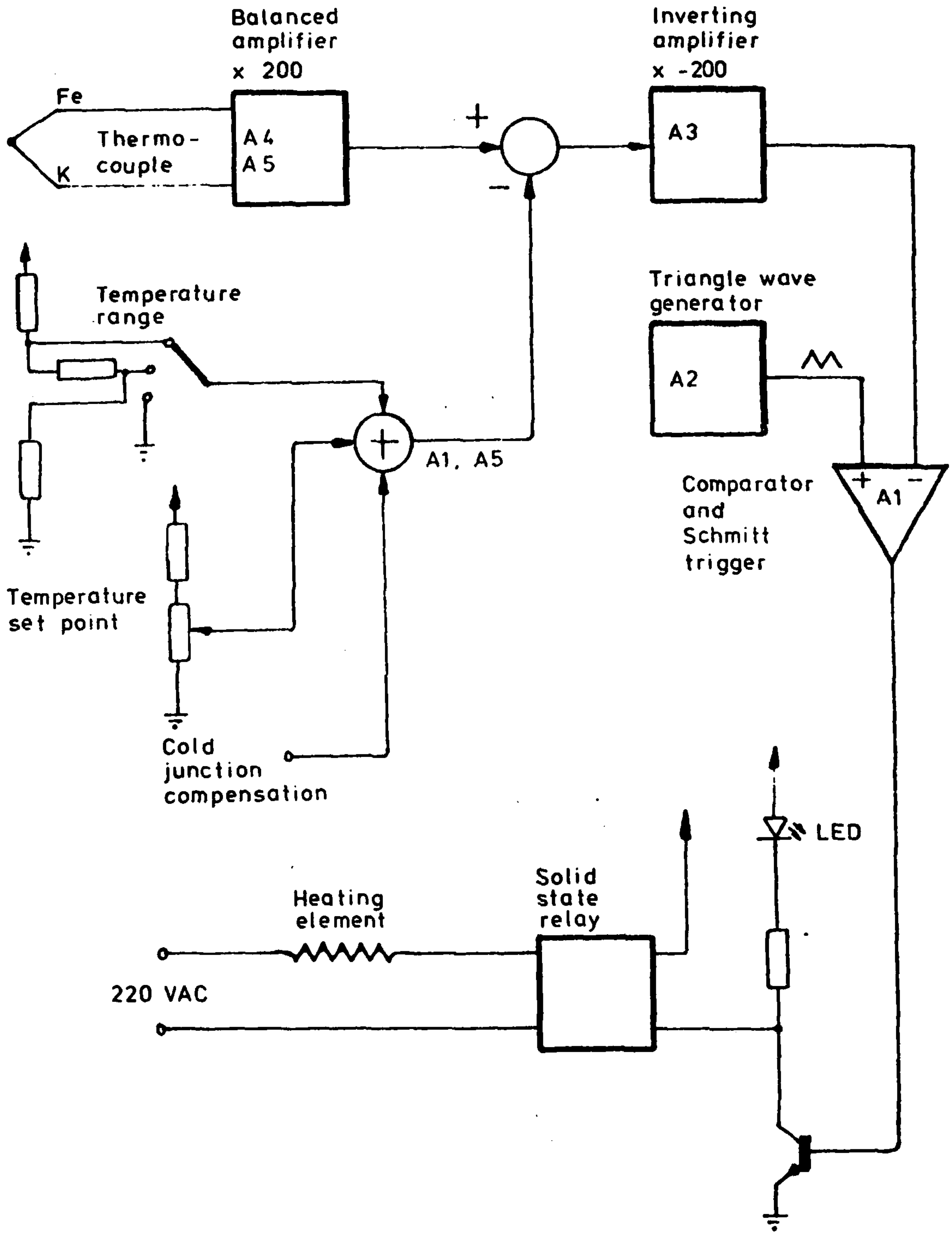


Figure 15. Temperature control: Principle of operation.

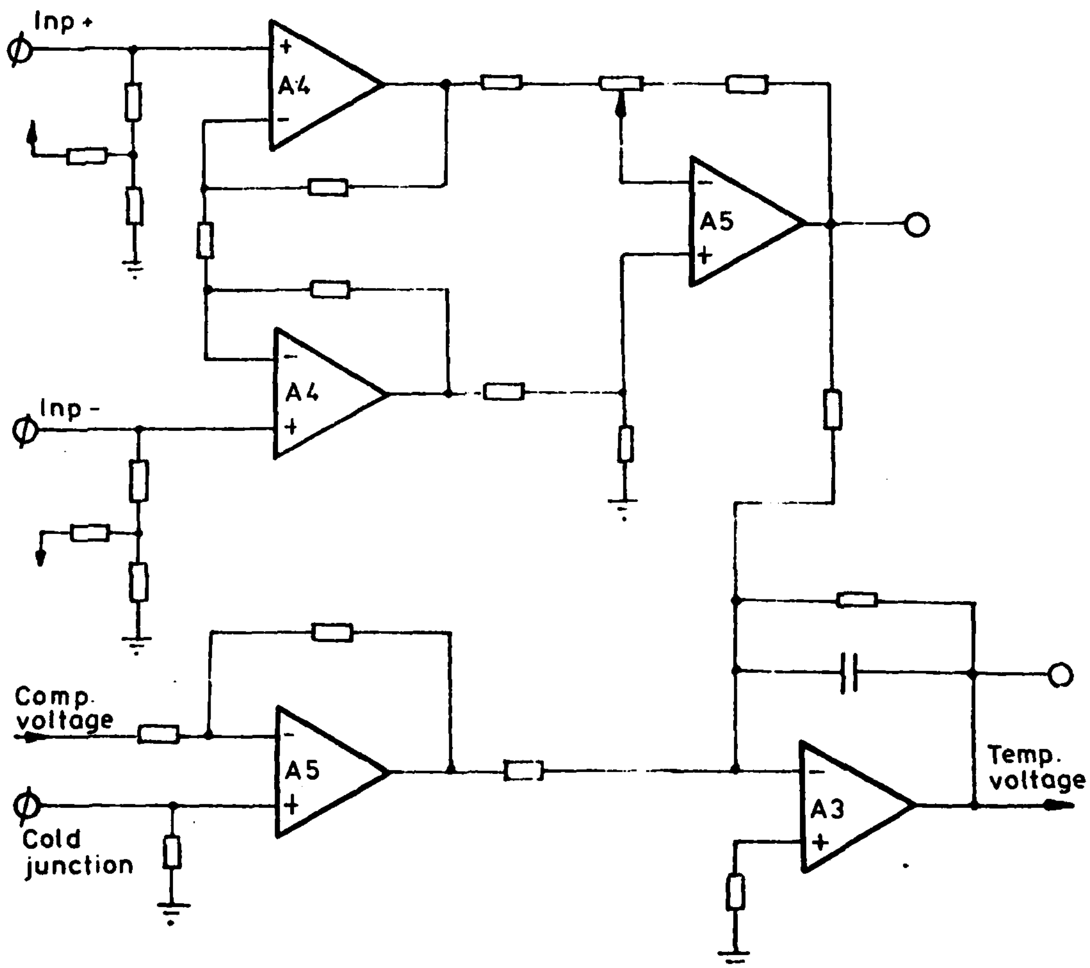


Figure 16. Temperature control: Wiring diagram 1.

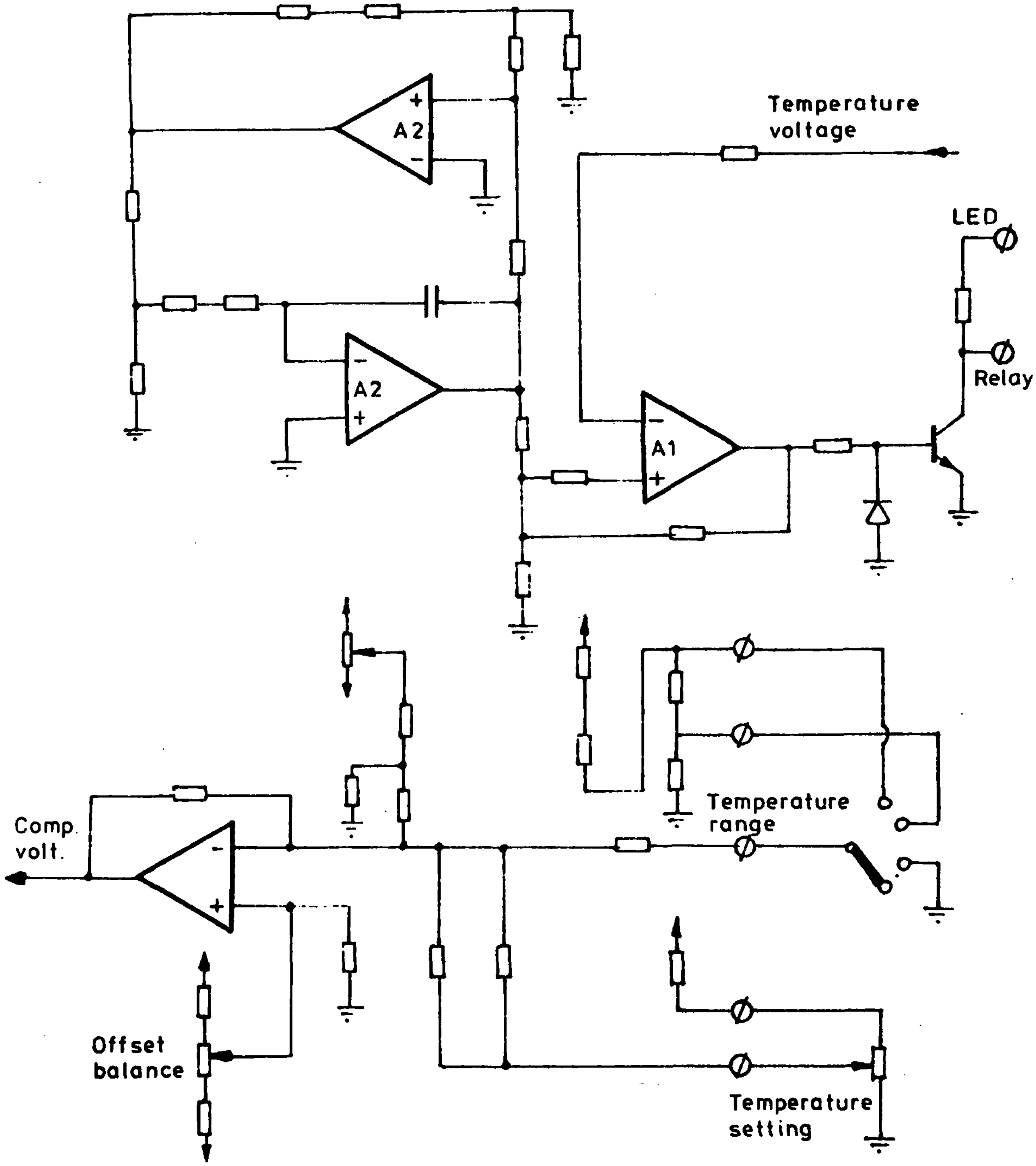


Figure 17. Temperature control: Wiring diagram 2.

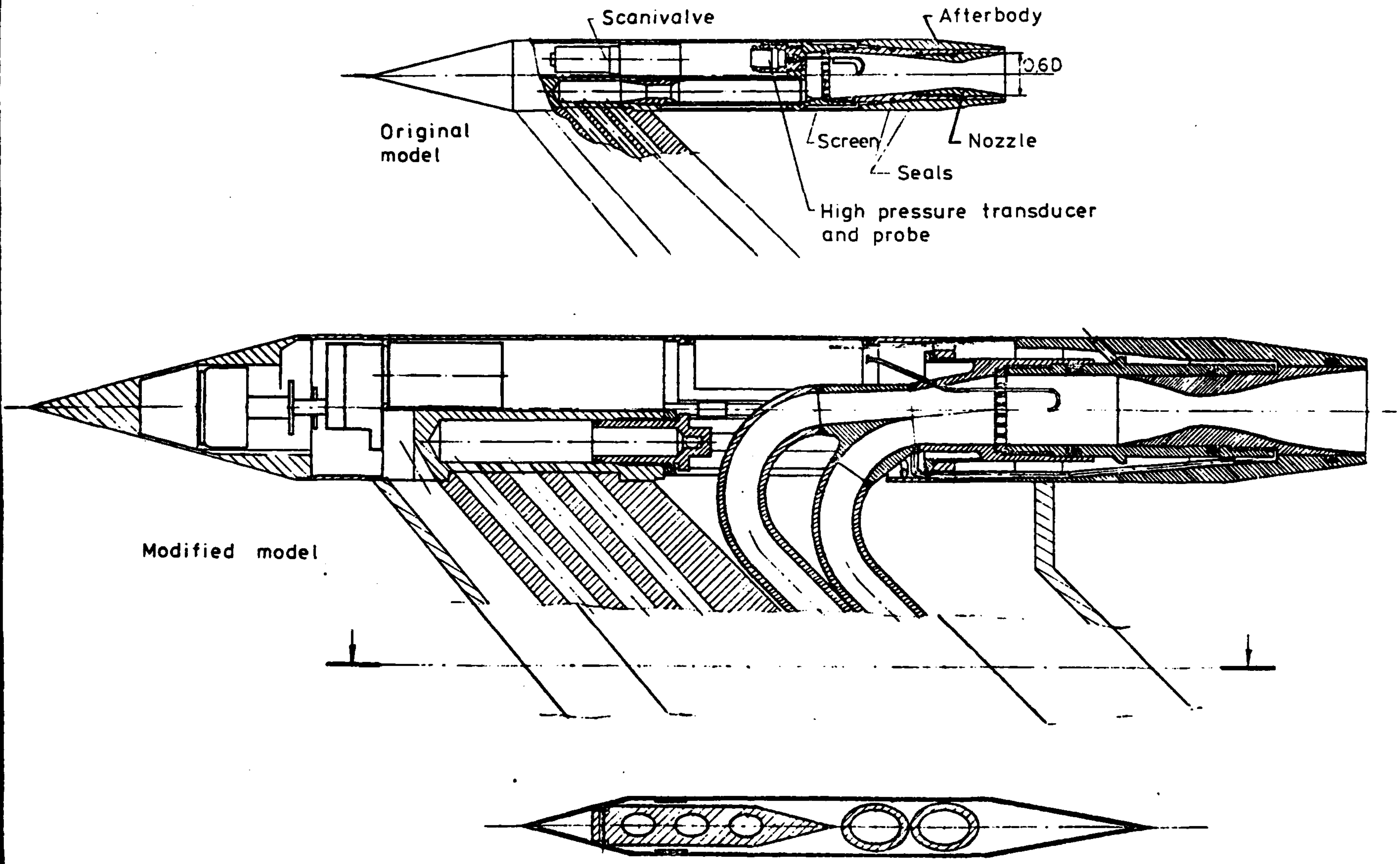


Figure 18. Model modifications.

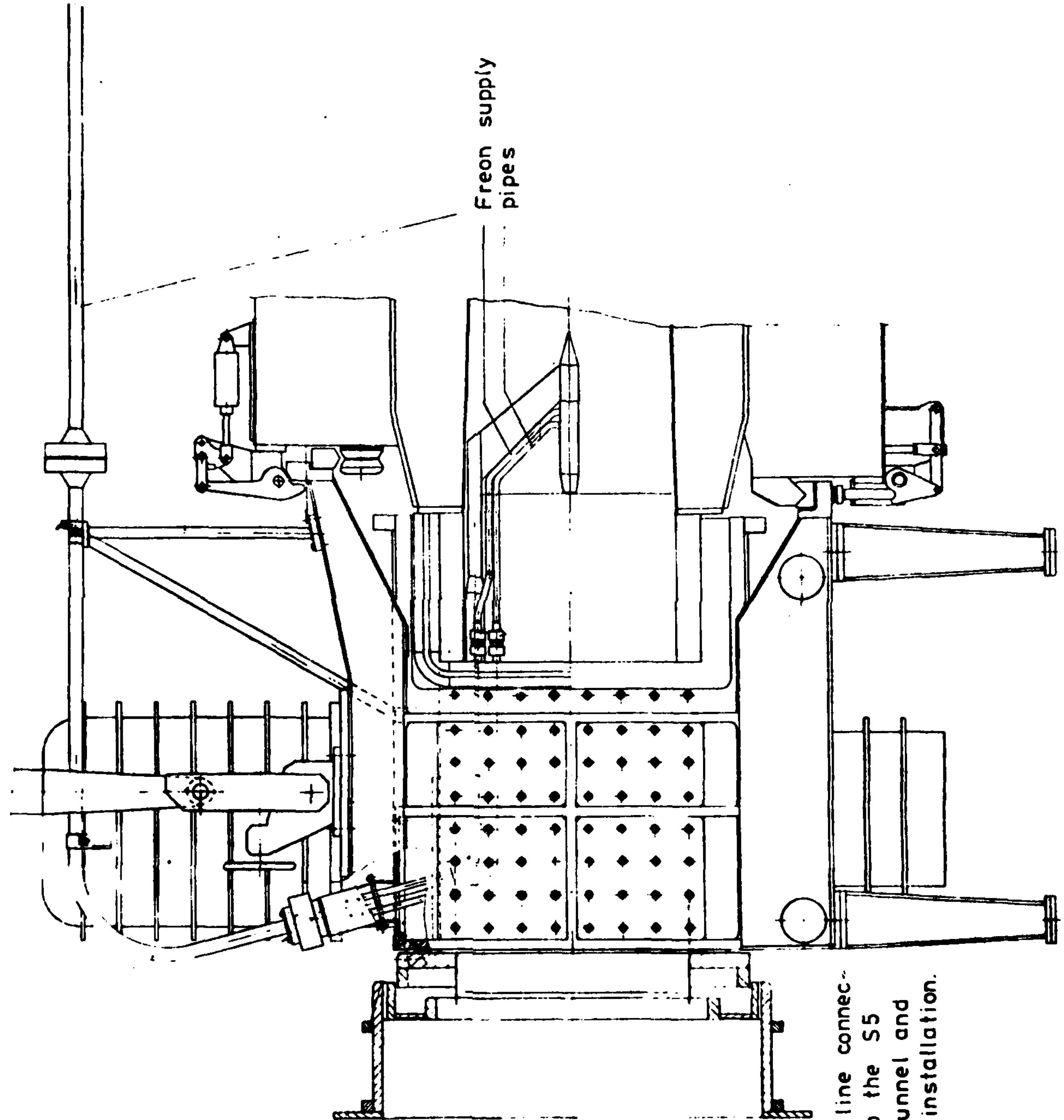


Figure 19. Freon line connection to the S5 wind tunnel and model installation.

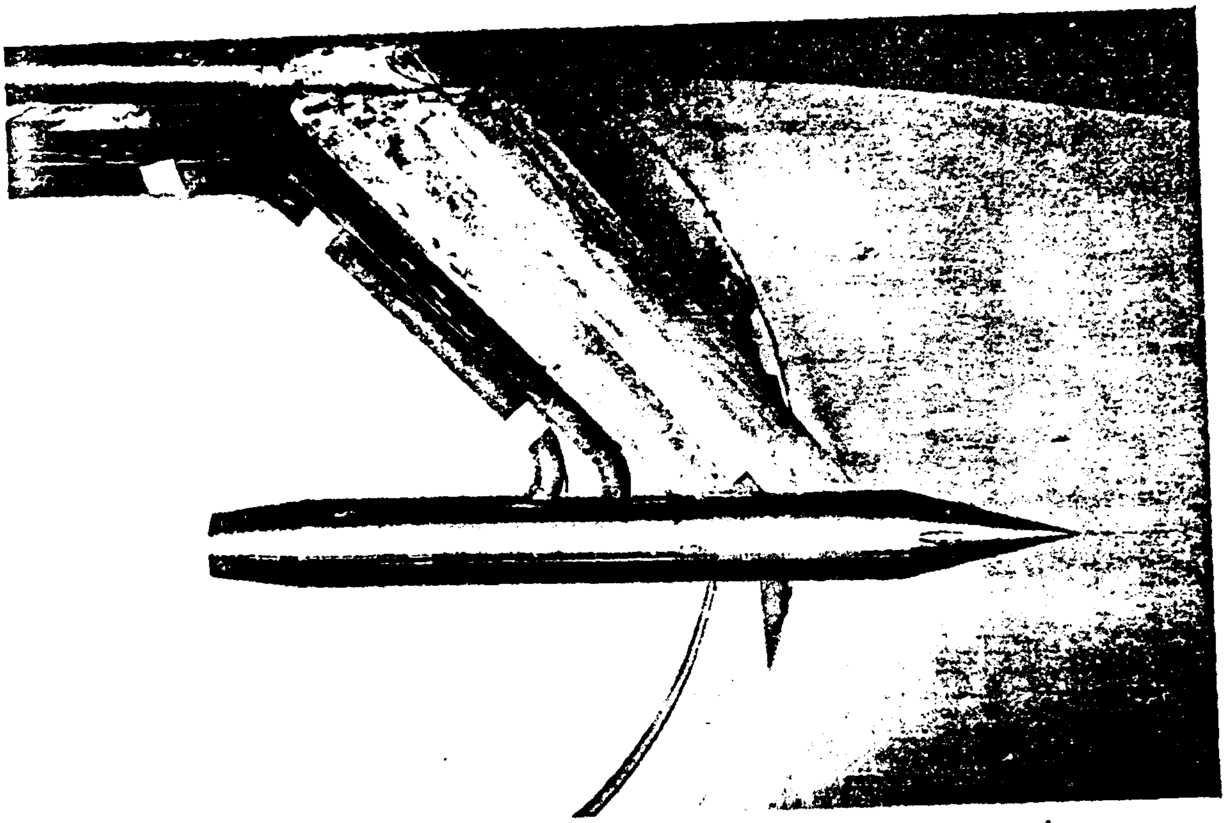


Figure 20. Model installation with leading edge fairing in position but with trailing edge fairing and side plates of the support strut removed.

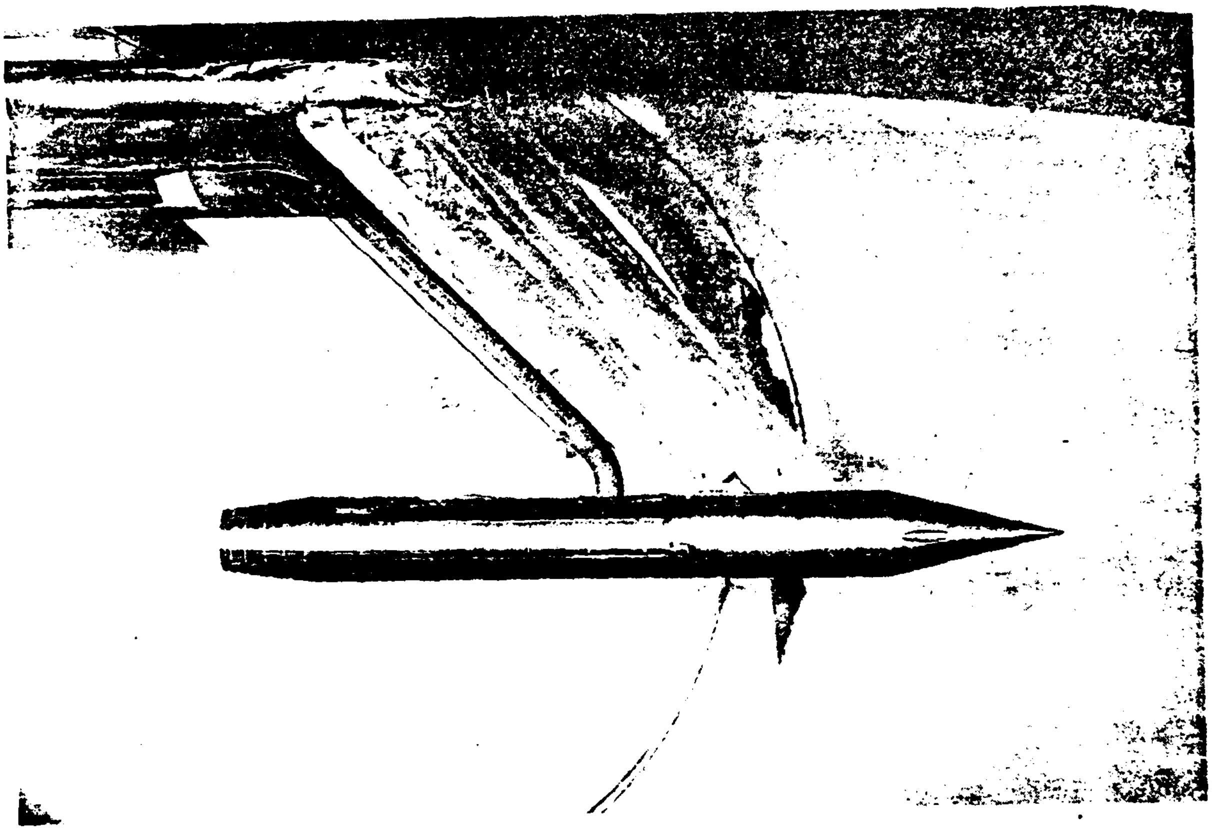


Figure 21. Model installation with leading and trailing edge fairings of the support strut in position but with side plates removed.

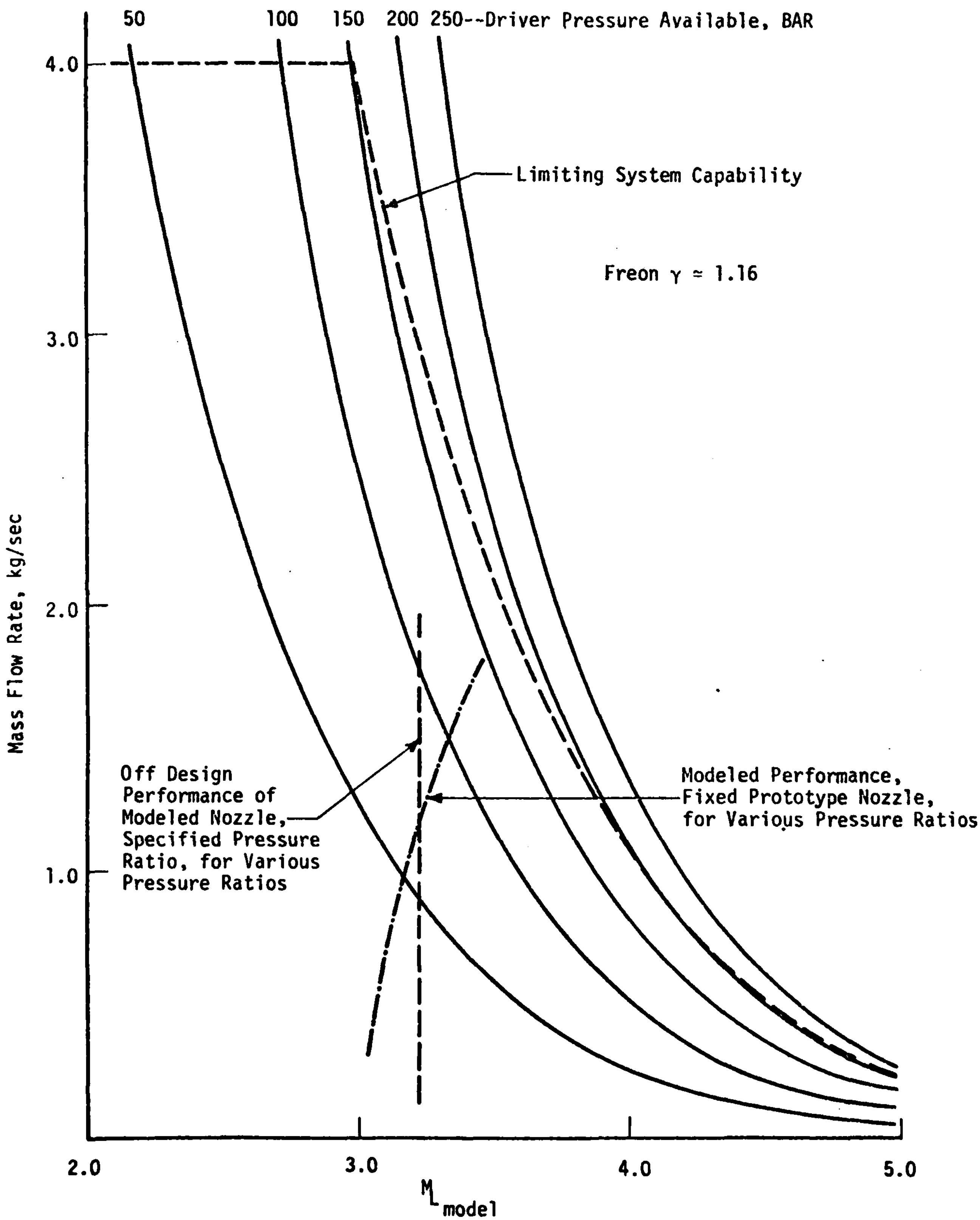
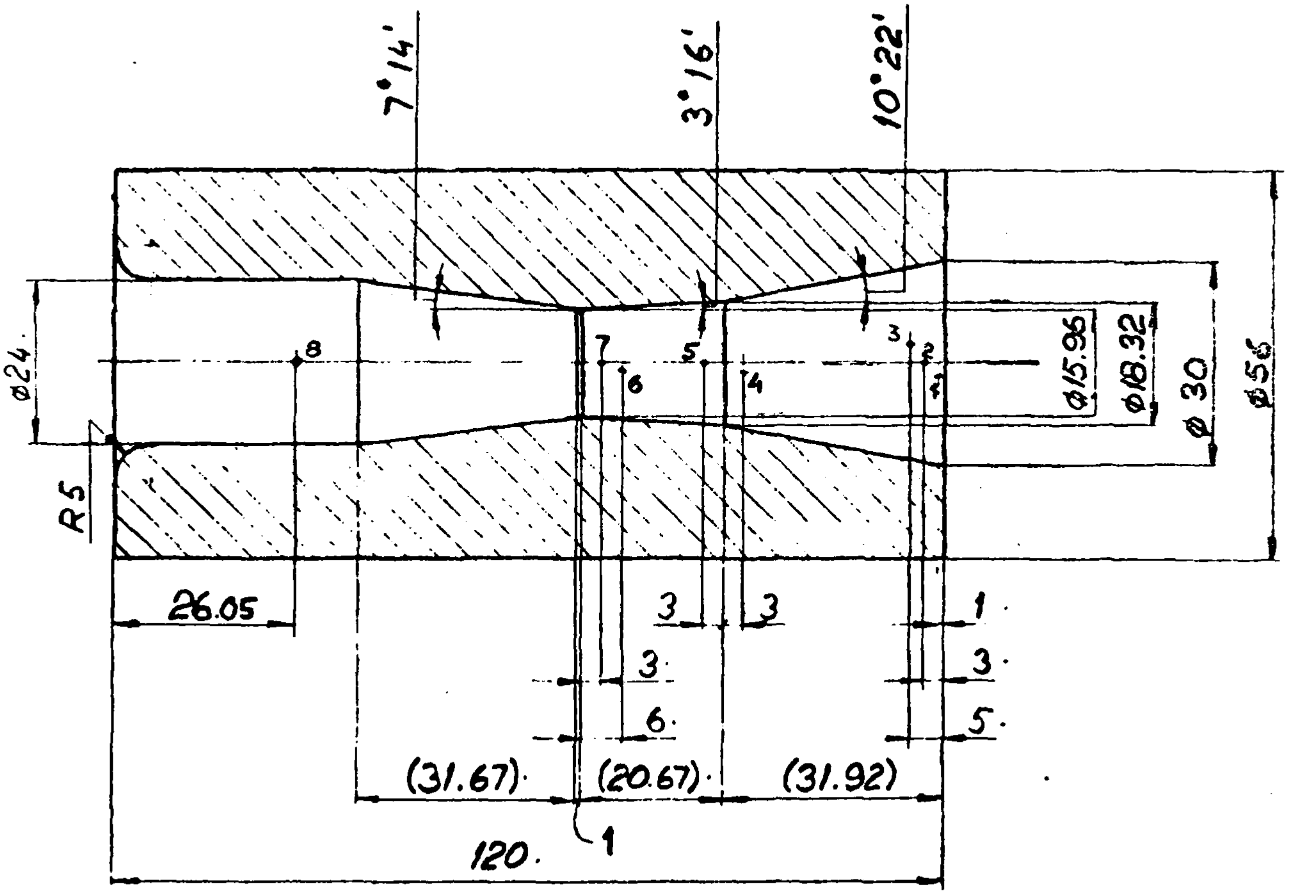


Figure 22. Modeled Performance and Off-Design Conditions



8 pressure taps (numbered 1-8) along the nozzle wall

Figure 23. Nozzle for calibration and analysis.

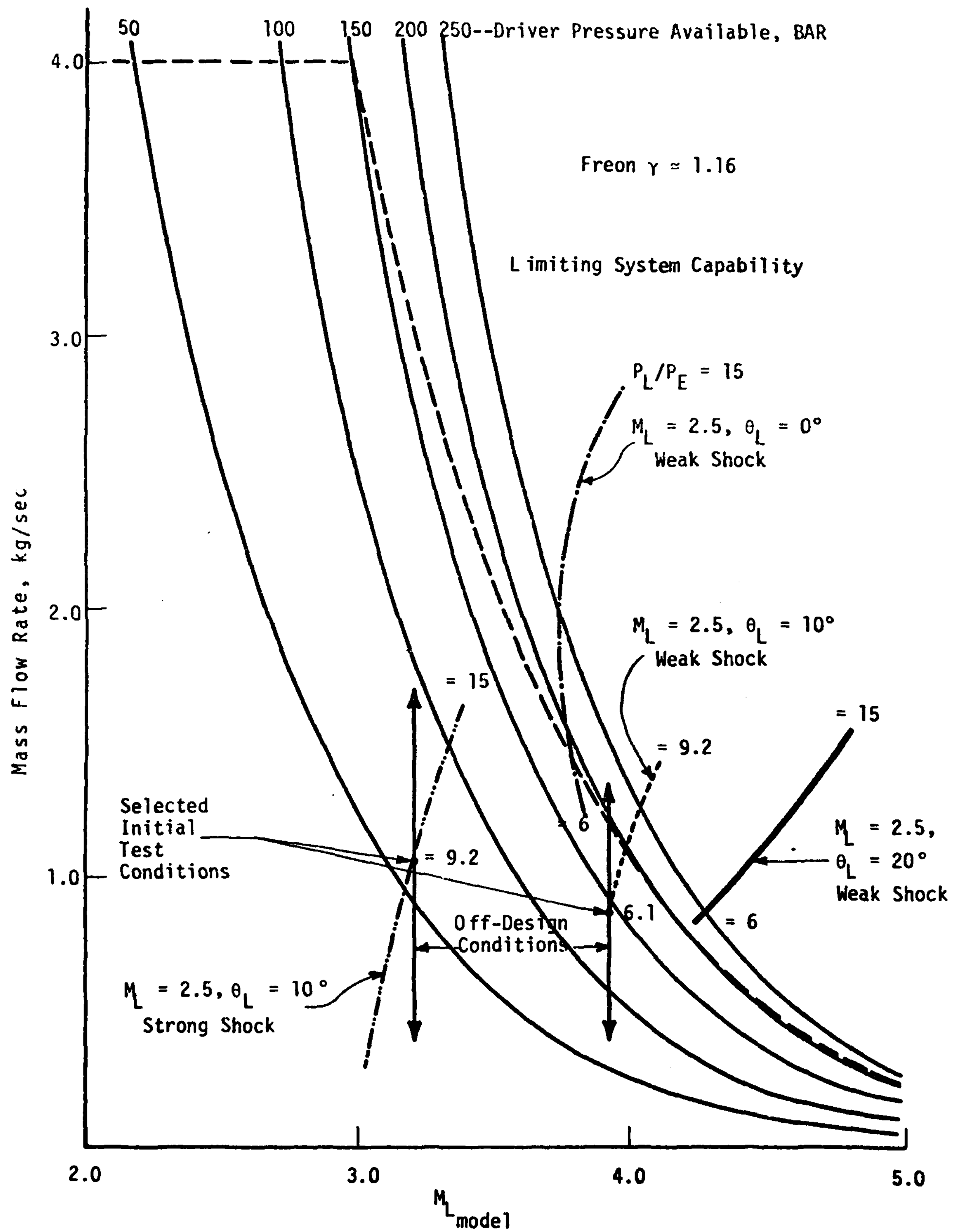
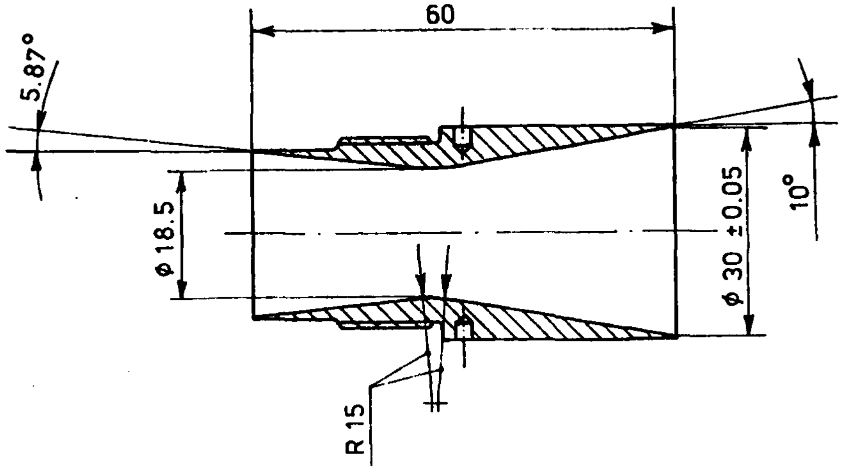
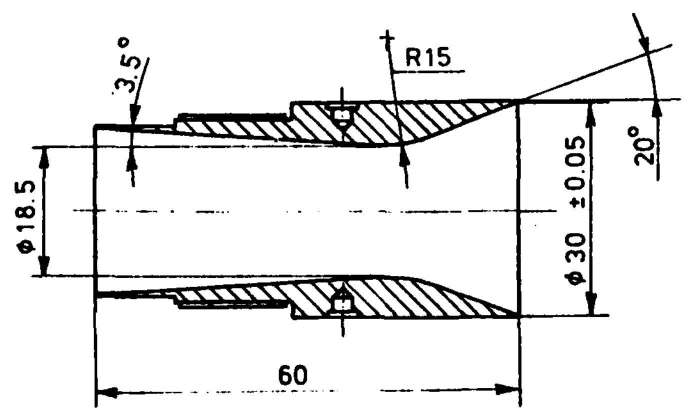


Figure 24. Modeled Performance and Test Configurations for Initial Test Program

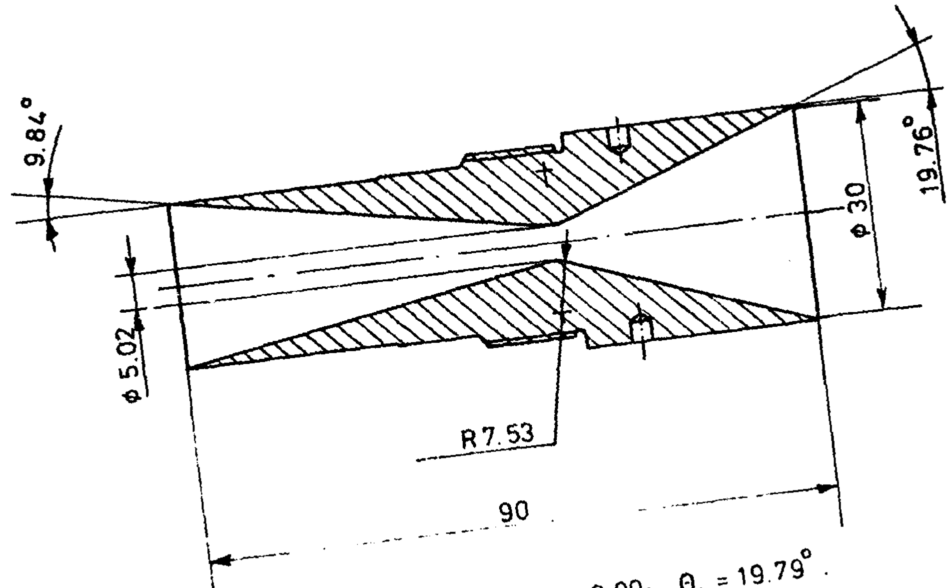


a) $M_L = 2.5$; $\Theta_L = 10°$.

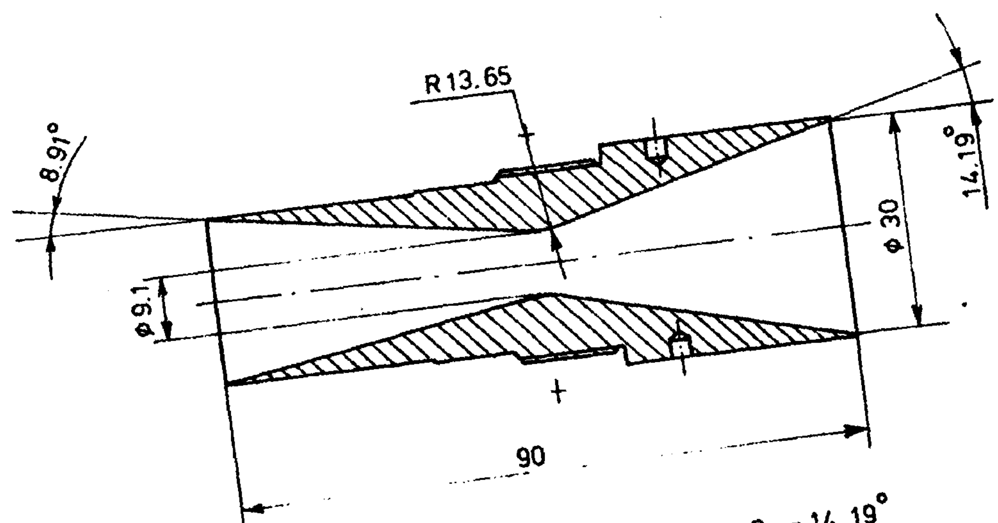


b) $M_L = 2.5$, $\Theta_L = 20°$

Figure 25. Nozzles for initial calibration tests.



a) Weak shock modeling. $M_L = 3.90$; $\Theta_L = 19.79°$.



b) Strong shock modeling. $M_L = 3.19$; $\Theta_L = 14.19°$

Figure 26. Nozzles for initial modeling tests.